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U. S. Naval Ordnance Laboratory
White Oak, Silver Spring 19, Maryland

NAVAL ORDNANCE LABORATORY MEMORANDUM 10771

30 March 1950

From: R. Stresau
I. Kabik
L. D. Hampton
To: NOL Files
Via: A. E. Robertson
D. E. Sanford
G. K. Hartmann

Subj: Firing Characteristics of Electric Initiators made by the Spraymetal Process. NOL-26-Re2b-222-5

Abst: Low energy electric initiators made by the spraymetal process have been investigated for their various firing characteristics. It has been found that for rapid pulse discharges the required firing energy is a function of the bridge volume and the time required to deliver the energy. The explosive particle size must be small to effect ignition but the loading pressure is of lesser consequence. A theory for the initiation of explosives by pulse discharges through a wire is given and from it there are calculated the activation energies of lead styphnate and lead azide. The reproducibility of initiators made by the spraymetal process is discussed. The required constant current for firing is given as a function of diameter but is shown to be dependent on bridge length also, due to heat lost through the bridge ends. The time to fire this type initiator is given as a function of the energy and the pulse duration.

Fwrd: This memorandum is intended primarily for the use of NOL personnel engaged in the design of devices using low energy initiators of the spraymetal type. While the data recorded herein are believed to be approximately correct in magnitude and fairly accurate insofar as they indicate trends, they should not be regarded as absolute. Many refinements in measuring techniques have been instituted since a large part of these data were recorded. Limitations are noted insofar as possible in the text.

Ack: The work discussed herein includes contributions of a number of people other than the authors. Some of the most important contributors are the following: Dr. H. J. Plumley, who is coinventor of the spraymetal method of applying bridges to electric initiators and who proposed some of the original concepts

from which many of the experimental methods were derived; Mr. C. W. Randall, whose ingenuity and diligence were largely instrumental in reducing the process to practice; Mr. A. M. Syeles, who refined the techniques and equipment for the etching of wire to the point where .0001 diameter and smaller tungsten wire were produced at the NOL several years before it was available commercially; Mr. L. E. Starr, Mr. J. N. Ayres, and Mr. F. W. Hayward, who devised, constructed, and calibrated instrumentation and apparatus used in some of the experiments; Mr. C. W. Goode, who constructed and calibrated instruments and did much of the experimental firing.

Ref: (a) NOLM 8696 - Method for the Fabrication of Low Energy Electric Detonators
(b) NOLM 7115 - Detonator Firing by Condenser Discharge
(c) NavOrd 90-46 - Theory of the Detonation Process (S-12635)
(d) OSRD-1986 - Determination of Explosion Temperatures (S-8347)
(e) Sci. Vol 79 p. 409, 1934
(f) AMF Rpt. No. 101.1R
(g) NOLM 10434 - Device for the Measurement of Times of the order of one microsecond
(h) NOLM 10398 - Primer test set Mk 173 Mod 0

Encl: (1) Plates 1 through 24
(2) Tables 1 through 5

INTRODUCTION

1. Since the spraymetal process (Reference (a)) was developed to the point where initiators could be produced in sufficient quantities for statistical experiments, a number of studies have been made of the effects of various factors upon the sensitivity or apparent sensitivity of initiators of this type. Some of the studies were made for design purposes, others as preliminary investigations of the hot wire sensitivity of various explosives and still others as investigations into firing circuits and firing circuit components. An attempt has been made here to systematize the data in such a manner as to indicate probable trends.

Construction and Preparation

GENERAL

2. The electric initiators discussed in this memorandum were made by the spraymetal process described in detail in Reference (a). By this technique sprayed molten metal is used to engulf the bridge wire ends, and fasten them to the contact prongs, and to simultaneously establish the bridge length by covering the initiator plug nose surface with metal except for a narrow strip which has been masked by the edge of a suitable shim. The length of the bridge approximates the thickness of the shim and where this length is referred to, the value given will be the shim thickness. After bridging, a charge holder is assembled onto the plug and the explosive pressed into place. Plate 1 is a diagrammatic sketch of the finished initiator. A few changes in design have been made since the publication of Reference (a) but none of them has been found to affect the firing characteristics of the initiators.

3. Most of the bridges used in the tests reported here were made from drawn and etched tungsten wire purchased from the Westinghouse Electric and Manufacturing Company at a nominal size of .00029 in. (diameter) with weight per unit length reputedly held within 5% of the nominal value. This wire was further reduced in diameter at NOL by an acid etching technique. The diameter of the wire etched at NOL was determined by resistance measurements. Some of these measurements have been checked by comparing with diameters obtained using a projection microscope with an overall magnification of 1200 X. The resistance ranges allowed for, various nominal diameters are shown in the following tabulation.

Nominal Diameter	Resistance Range
0.00014 in.	140-150 ohms/in.
0.00010 in.	250-300 ohms/in.
0.00009 in.	300-400 ohms/in.

These tolerances were based on the practical limitations imposed by the etching process at the time of the experiments. It was not unusual for the bulk of the wire in a particular batch to run close to one of the extremes of the range, and it sometimes occurred that the values fluctuated throughout the entire range. For this reason, results obtained in different tests are not always directly comparable. When an investigation was made of a particular phenomenon, it was the practice to bridge all of the plugs to be used and to then randomize them; before loading if the test was to be of loading factors, and after loading when firing conditions were to be tested.

Preparation of Explosives

4. Many explosives, as received, have a mean particle size that is so large compared to the bridge wire diameters under consideration that intimate contact between explosive and bridge wire upon loading is virtually impossible. Indeed the bridge wire could be made to burn out without initiating the explosive. For this reason it was found necessary to grind the explosive. This grinding has been performed in a small ball mill using 5/32 in. stainless steel balls. In the early experiments a standard two ounce bottle was used as a mill. The bottle was about an inch and a quarter inside diameter and turned at 70 RPM. More recently a special metal container has been designed which has approximately the same inside diameter but turns at only 48 RPM. (The container is rotated by a pair of rolls, the difference in RPM is due to the difference in outside diameters.) In order to compensate for this change the standard grinding time has been increased from 16 to 24 hours. In general, the standard charge is 20 gms. of stainless steel balls and 2 gms. of explosive. The explosives are ground wet. Since with most explosives no difference was found between results where water was used and those where chloroform was used, the latter was used in most of the work because it is more easily removed after the grinding. In some cases where compatibility is involved substitute materials are used for the.

stainless steel balls, the aluminum grinding bottle and the chloroform. After grinding, the explosive is dried on a Beuchner funnel before loading.

Loading

5. The explosives are, in general, measured with a scoop which holds roughly five milligrams of lead styphnate. The loading pressure is applied by means of an arbor press modified to indicate the force by means of a leaf spring-dial indicator arrangement. This device is accurate to within two or three percent. A greater error probably results from the friction of the ram in the funnel. The diameter of the charge cavity is, in most cases 1/16 in. The usual practice is to use a dead load of 10.5 pounds, which gives a theoretical loading pressure of 3,400 psi. Frictional resistance of the order of one pound, which probably is not unusual could thus cause an error of about ten percent. That such errors are not serious may be seen from data appearing in a later section.

Drying of Initiators

6. The drying of the explosive on a Beuchner funnel is not complete. The small amount of moisture or other liquid which remains in the explosive improves the handling properties of the explosive and probably reduces the friction and static sensitivity. To remove this remnant of liquid the initiators are dried overnight at 50°C. In the earlier experiments this was done using circulating dry air, but later a vacuum oven was used. No significant difference was noted between air and vacuum dried initiators. In some instances the explosive was dried in the oven before loading. There is no evidence that this alters the results.

Experimental Technique

Firing Circuit

7. Most of the data given here were obtained using a simple condenser discharge circuit consisting of a power supply, a condenser, and a double throw switch by which the condenser can be switched from the power supply which charges it to the initiator, through which it discharges. (See Plate 2.) Ideally, such a circuit delivers 86.5 percent of the energy stored in the condenser in a time equivalent to RC; or 98.2 percent in 2 RC; where C is the capacitance of the condenser and R the resistance of the initiator. The energy stored in the condenser is given by 0.5 CV^2 where V is the potential to which the condenser is charged. These ideal computations are based upon the following assumptions:

(a) The circuit resistance is that of the initiator only
(b) The circuit inductance is negligible
(c) Once closed, the circuit remains closed until the significant part of the energy has been transferred
(d) The resistance of the initiator is constant

The last of these assumptions is obviously untrue while the validity of the others varies with the test conditions. The extent of these variations

and their effects will be discussed in some detail in a forthcoming report. A few remarks here may be useful in evaluating the data which are reported in the present memorandum.

Resistance Losses

8. Although precautions are taken to keep the circuit resistance as low as possible, contact resistance in the firing chamber safety interlock, and various other connections, amount in some cases to as much as 0.1 to 0.2 ohms. Thus, for initiators whose resistance is of the order of one ohm, the loss to extraneous resistance is quite appreciable. These losses are considerably reduced by the increase in resistance of the bridgewire during firing. The contact resistances may reduce, to some extent, when heavy currents are flowing.

Switches

9. The time-resistance function of the switch during the first microsecond after closure has been the subject of much speculation. It has been pointed out that the original contact area, in most cases, must be rather small. The times here are so short as to preclude the confident use of even the DuMont 248 oscillograph in measuring resistance as a function of time. The best information at hand which gives some indication regarding the magnitude of energy dissipation due to switch resistance is that which was obtained by replacing the initiator with the heater of a vacuum thermocouple. The thermocouple drives a Grashof fluxmeter. The deflection of the fluxmeter has been found to be directly proportional to CV^2 and independent of RC even for RC values as low as a tenth of a microsecond or less. Tests of this kind have been made using a wide variety of switches, both commercially obtained and laboratory fabricated. A number of switches were found to have very good characteristics at low voltages, but to give occasional low readings when the voltage was increased much above 25 volts or so. These low readings, which may be traceable to pre-arcing in some cases, and to high resistance films in others increase in frequency of occurrence as the voltage is increased. A vacuum relay has been found which is evidently free from this effect up to 3000 volts. Frequent checks are made of the firing circuits, using the vacuum thermocouple and fluxmeter and it is believed that switch losses are small, in general, compared with the deviations of the firing energies which are quoted in the accompanying data.

10. Most switches chatter during closure. Measurements were made of the time between the first closure and the first opening by means of a cathode ray oscillograph and it was found that this time was highly reproducible for the switches which were used. Care was taken to use switches for which this time was long compared with the firing pulse.

Circuit Inductance

11. Perhaps the most serious defect of the firing circuits used to obtain the data herein reported is the inductance of the leads. Considerations of safety and flexibility have resulted in a general circuit design which has considerably more inductance than could be realized in a special circuit with no safety features. A measurement of a typical circuit showed the inductance to be 4.5 microhenries. This inductance might be expected to have two effects: the loss of energy by electromagnetic radiation and the distortion of the pulse shape and duration. The tests mentioned in paragraph four, above, indicate that the radiation losses are negligible. However, the effect of the inductance upon the pulse shape and length may be quite appreciable. No work, to date, has cast much light upon the effect of pulse shape but it has been well established, both in the experiments herein reported and in those reported in Reference (b) as well as by others, that pulse length can have a very important affect upon the energy requirement of an electric initiator.

Damping

12. A circuit involving capacitance, resistance, and inductance may be either overdamped, critically damped, or underdamped. It can be shown that circuits in the critically damped and overdamped conditions (where $\frac{CR^2}{4L}$ is equal to or greater than one) deliver most of their energy to the resistance in a time equivalent to RC but that underdamped circuits have time constants proportional to L/R and independent of RC. The underdamped discharge is, of course, oscillatory and the energy is delivered to the resistance in several pulses.

Bridge Resistance Changes

13. The foregoing is a discussion of condenser discharge through a constant resistance. Most of the initiators discussed in this memorandum had bridges of tungsten which has a high thermal coefficient of resistivity. The peak values have been calculated to reach eight or ten times the resistance at room temperature. Experiments of several types, which will be described later in this report, indicate that the mean effective resistance of the tungsten bridges during firing is of the order of two to three times the cold resistance. Both the peak and mean resistances are functions of the peak temperature which varies appreciably as will be seen later. The substitution of such a mean effective resistance is a useful approximation in estimating damping coefficients, time factors, and impedance matches.

Distributed Capacitance

14. No measurements have been made of the distributed capacitance of the circuits, but even the largest estimate is less than 100 micromicrofarads which is negligible compared with the condensers used in the test discussed herein.

Firing Circuit Summary

15. All of the above deviations from the ideal circuit (except that due to the distributed capacitance, which is negligible) have one or both of two effects; the dissipation of part of the energy ($CV^2/2$) at points other than in the initiator bridge, and the increase of the pulse length to periods longer than RC. The first of these does and the last may increase the apparent energy requirement of the initiator, while neither can result in a decrease in this quantity. It can thus be concluded that the energy requirements quoted are not lower than they would be under ideal conditions. The designer of circuits, if he knows the output of his firing mechanism, can be confident (with the exceptions to be noted below) of obtaining at least the calculated reliability of a circuit-initiator combination, but the probability of primers firing on spurious signals impressed directly across the bridge is probably greater than might be calculated from the data.

Theoretical Considerations

16. While it is not the purpose of this memorandum to attempt the derivation of a rigorous theory of the hot wire initiation of explosives, it might be worth while at this point to discuss some of the factors involved.

The simplest set of assumptions which might be made are that (1) the explosive has a definite "ignition temperature" above which it will always initiate and below which it will remain unchanged, (2) the firing pulse is very short compared to the cooling time of the wire and (3) all the energy in the pulse is delivered to the wire so that the maximum temperature reached by the wire is the quotient of the energy in the pulse by the thermal capacity of the wire. On these assumptions, the energy required to initiate a propagating reaction is proportional to the volume of the wire for systems of identical materials but varying dimensions and is independent of all electrical variables. These assumptions are a rather good first approximation for predictions of performance within a limited range but the "ignition temperature" assumed must be much higher than those determined by such standard procedures as immersion in metallic baths, dropping on hot plates, etc. Of course it always is possible to manipulate the characteristics of the electrical circuit so that the second of these assumptions is true. The first of the above assumptions, while useful over a limited range, may be misleading where order of magnitude changes of wire size are considered.

17. Consider a relatively large mass of explosive, a limited portion of which has been raised to a high temperature compared with the larger mass. If the material behaves in accordance with the Arrhenius equation, the reaction rate is proportional to $Ze^{-E/RT}$ where E is the activation energy, R is the gas constant, T is the absolute temperature and Z is the collison number. At most of the temperatures herein considered, thermal losses can be considered to be proportional to the temperature

gradient and to the area of the surface through which the heat is lost. For geometrically similar masses, the surface-volume ratio is inversely proportional to the size (one of the linear dimensions). Then for any given size of the heated portion, there will be a corresponding temperature at which the losses just balance the heat generated by the reaction. If the temperature is lower, the reaction will die out. If it is higher, the reaction will accelerate. From the above considerations, it is obvious that this critical temperature is higher for smaller heated portions. It can also be seen that the change in critical temperature with size is smaller for explosives of higher activation energy (E). The case of a spherical heated portion has been considered by Gamow and Finklestein (Reference (c)) who have derived a differential equation which was solved mechanically for a few points. The case of the long cylinder has not, to the writers knowledge, been solved. It was noted, however, that the numerical solutions mentioned above satisfy, very nearly, the equation--

$$\ln a = \frac{E}{2RT_c} + k \quad \text{(equation 1)}$$

which also is a close approximation of the solutions to the one, two, and three dimensional cases of a finite mass of explosive which is brought into contact with an infinite reservoir of heat, where a is a linear dimension, k is a constant, and T_c is the critical explosion temperature (absolute). This suggests that the same equation might apply to the two dimensional transient case. Assuming this equation to apply, a plot of the logarithm of the diameter versus the inverse absolute critical temperature should give a straight line the slope of which is equal to 1/2R times the activation energy. Application of this equation to the determination of the activation energies of lead styphnate and lead azide will be given in a later section.

Procedure and Analysis

18. The tests upon which the data given in this report are based were made by the Bruceton method of testing which is discussed in more detail in Reference (f). In the greater part of the tests recorded in this report the initiator being tested was subjected to the discharge of a variable condenser which was charged to a fixed potential. The capacitance of the condensor was varied so that the energy delivered to the initiator was one or another of a series of steps or energy levels. The essential feature of the Bruceton method of testing is that each initiator is tested at a single energy level and the result of the test recorded as a success or failure as the case may be. If the trial is a failure the next initiator is tested at the next higher level. If a given trial is a success the energy given the next initiator is that of the next lower level. The levels at which successive initiators are tested will fluctuate about the point at which fifty percent of the initiators would fire. Plate 3 is a reproduction of a typical completed

test sheet. The steps can be located so that either the energy values themselves or the values of some function of the energy, say F, are equally spaced. If, for each value of the energy used, the percentage of initiators which will fire at this level is plotted against F as an independent variable a frequency curve will result. In carrying on this test one usually attempts to make a choice of the function F in such a manner that the resulting frequency distribution is normal. This is especially desirable if any attempt is to be made to study the variation present as one must do if he is to estimate the accuracy of his results. In these tests the logarithm of the energy was selected as the function F. It seems reasonable to suppose that this choice is better than that of using the energy itself. The frequency distribution of minimum firing energy of the initiators with respect to the energy itself would be limited to non negative values and since the normal distribution curve extends from negative infinity to positive infinity it is clear that using the energy itself as the independent variable will not give the normal distribution curve. It also seems clear that the normalizing function F should be one which transforms zero energy into a negative infinity and leaves positive infinity unchanged. The logarithm is a function which has this characteristic and has been used by many investigators in the field of explosive sensitivity measurement for this purpose. The results obtained in tests appear to support this choice of variable. One such test was made using initiators having a tungsten bridge of 100 micro-inch wire and loaded with lead styphnate. Between forty and fifty initiators were tested at each of several levels. The results of this test were analyzed by the Probit method Reference (e) using the energy as the independent variable and also when using the logarithm of the energy as a normalizing function. The number of initiators which would be expected to fire was computed on the basis of each assumption. The fit was tested by calculating the value of Chi Square for each assumption. These results are given in Table I. The values of Chi Square are computed from the Probit analysis as described in Reference (e). If the predicted values given in the table are compared with the observed values with the first three lower energy values grouped together and the value of Chi Square is computed the result is 0.255 for the case of prediction from the energy itself and 0.082 if the logarithm of the energy is used. Plates 4 and 5 are graphical representations of the above calculations.

19. The Probit method of analysis consists of a change of the dependent variable so that the accumulated frequency curve is changed from an S curve to a straight line if the frequency distribution is normal. The predictions shown in Table I are made by finding the equation of the best fitting straight line as given by the theory of least squares and then calculating points on this line.

20. For any sample which has been tested by the Bruceton method it is possible to test the assumption of normality. This test has been applied to several such samples and the results indicate that this assumption is justified when the logarithm of the energy is used as the independent variable. Plates 4, 5, 6 and 6A are graphical representations of the

above calculations. Plates 4 and 5 give the expected firing probabilities in terms of probits. Plates 6 and 6A give the same information in terms of percentage. The upper and lower curves give the 95% confidence limits for the firing probability. These curves correspond with the limits given in Table I.

21. Results of these tests are subject to sampling error as in any method of testing. In particular the estimate of the standard deviation is subject to considerable error if the sample size is less than about fifty. Since this is the case in many of the tests reported here too much confidence cannot be placed in the results. It is thought, however, that the results given herewith are reliable as to orders of magnitude and will prove useful as a preliminary estimate of the quantities involved.

22. Although an attempt was made to eliminate all variables except those being studied, this was not always possible. Both the explosives and the circuits used may be affected to some extent by the weather conditions. The magnitudes of any such effects have not been measured but there is qualitative evidence of their existence. Some commercially obtained wire is uniform for a sufficient length to create the illusion that continuous checking is unnecessary, an illusion which has been dispelled. These together with some of the other variables mentioned elsewhere in this memorandum are probable reasons for the inhomogeniety which was sometimes observed among seemingly similar lots of initiators in some of the earlier experiments. When a specific effect was under study it was the practice to prepare a large number of initiators which were randomized down to the point where the effect to be studied came into play. Thus effects can be studied which change the energy less than the unavoidable variations between lots.

Results

Dimensional Factors

23. Initiators were made with bridge wires of a variety of diameters and lengths. The mean energy requirements of a number of these, loaded with lead styphnate are tabulated in Table II, and presented graphically in Plate 7. At first glance, the correlation between the volume of the bridge and the energy requirement is apparent. Further inspection will reveal that smaller wires, as predicted by theory, have a higher energy requirement per unit volume than larger wires. The apparent negligibility of this effect in the results with the "Tophet C" wire (see Plate 8) may be attributed to either experimental error or to inaccuracy of the assumption that both samples of wire have the same resistivity. It will be noted that, in addition to the increase in energy per unit volume with the decrease in diameter as predicted by reaction kinetics, there is an increase with reduction of length. This may be attributed to a number of factors which operate simultaneously. Heat losses through the ends of the wire, poor contact between the spraymetal and the bridge, and external circuit resistance all contribute. The relative importance of these factors cannot be readily assessed since they all operate in the same direction.

Circuit Factors

24. The energy required to initiate an explosive by means of a hot wire is a function of the rate at which the energy is applied, unless it is applied in a time which is negligibly short as compared with the cooling time of the wire. This can be illustrated by the obvious fact that, if the energy is applied slowly enough, initiation will never occur. Since most energy sources are subject to limitations regarding power output as well as energy per pulse, information regarding these relationships is essential to the rational design of electric fuzes, etc. Such information is perhaps even more important to the theoretical interpretation of results. A number of experiments were made in which the capacitance for 50% firing was determined at each of a series of fixed voltages. The results of such experiments are shown on Plate 9. It will be noted that, for the larger two sizes of wire, the energy becomes independent of the voltage above 14 volts. Data on the smaller wire beyond this voltage becomes somewhat less reliable because of the small capacitance needed. The shape of the curve, however, indicates that it will become very nearly parallel to the constant energy lines a short distance off the graph. Similar results are plotted on other coordinates on Plates 10 and 11. Perhaps the clearest interpretation is that illustrated on Plate 10 where a minimum energy and a minimum voltage are the asymptotes of a hyperbolic curve. The effect of pulse shape has not been investigated but experiments with high inductance circuits indicate that results for oscillatory circuits are analogous to those for damped circuits of the same decay times. On Plate 12 is plotted energy as a function of decay time. It will be noted that the results for damped and oscillatory discharge make a good fit to the same curve. Although there are too few points to be conclusive, the indication is that for practical considerations the pulse shape affects the energy requirement only to the extent that it affects the time required to deliver the significant part of the energy. A rigorous theoretical approach would undoubtedly reveal a more complex relationship. Experimental techniques have not advanced to the point where such calculations could be checked.

Effective Resistance

25. Most of the initiators discussed herein have tungsten bridges. Tungsten, like most pure metals which are good conductors, has a rather large thermal coefficient of resistivity. In the cases of the smaller wires, the resistance corresponding to the calculated peak temperature (on the basis of negligible heat loss during the discharge) is of the order of ten times the cold resistance. The effective resistance is obviously somewhere between the cold resistance and this calculated peak. On the basis of negligible losses during the discharge, the effective resistance should be very nearly midway between the cold resistance and the peak resistance since the resistance is a direct linear function of the energy. Two different types of experiments were run to check

these assumptions. In one a variation on an unbalanced bridge ohmmeter was arranged so that a vacuum thermocouple-fluxmeter combination could be substituted for the galvanometer. A calibration was made with a decade resistance as one leg of the bridge with pulses of various magnitudes. A number of initiators were tested using pulses of such magnitudes that the initiators received approximately their threshhold firing energy. The resistances measured in this manner were roughly three times the cold resistances of the initiators. The other experiment consisted of a series of Bruceton type tests as described in an earlier section in which fixed resistances were placed in series with the initiators. Test conditions were varied in such a manner as to keep the RC time as nearly constant as possible for all of the tests. The energy requirement of the system including the initiator and the fixed series resistance was found to be a direct linear function of the external resistance from which the effective resistance of the initiator could be calculated. (See Plate 13.) This experiment yielded a value of 3.18 ohms for a lead styphnate loaded initiator with a tungsten bridge .00029 inches in diameter by .030 inches long. The theoretical cold resistance of these initiators is about 1.1 ohm and the measured resistance is usually of the order of 1.4 ohms. The calculated peak resistance is of the order of six ohms.

Explosive Materials

26. A number of primary explosive compounds and mixtures have been used as flash charge materials. Results obtained with a number of these appear in Table III. It will be noted that, although the materials are listed in the order of decreasing sensitivity with the smaller bridgewire, the values with the larger wire include a number of inversions of this order. These are predicted by the theoretical considerations discussed in paragraph 16. On Plate 14 more detailed data for lead azide and lead styphnate are plotted according to equation (1) which predicts that the slopes of the lines are equal to $\frac{1}{2R}$ times the activation energies. The activation energies for lead styphnate and lead azide determined from the best lines obtained by the method of least squares are 57,300 and 21,775 calories per mol respectively as compared with Henkins figures of 58,800 and 21,200 cal per mol. (see Reference (d)) This rather close agreement, taken alone, would tend to confirm the validity of equation (1). There are, however, a number of reasons to believe that the agreement is coincidental. More closely controlled experiments, for example, wherein a number of the indeterminate factors inherent in the electric initiators of the construction discussed herein are greatly reduced or eliminated, give much lower activation energies. These experiments indicate that the most important of these factors are associated with the low length/diameter ratio of the larger diameter bridgewires. These factors (external losses, end effects, etc.) tend to increase the energy requirement of the larger wires more, proportionally, than the smaller wires. If neglected, these factors tend to decrease the apparent temperature differential between different sizes of wire and hence increase the calculated activation energy.

27. On Plate 15 the mean energy requirement is plotted as a function of the bridgewire diameter for a few explosives. It will be noted that the temperature corresponding to the mean firing energy for lead styphnate, which, according to Henkin (Reference (d)) has an activation energy of 58,800 calories per mol, varies much less with wire diameter than does that for lead azide (E = 21,200) and mercury fulminate (E = 20,200). The assurance with which Plate 15 can be relied upon for the prediction of results is indicated by the points for lead styphnate which are numerous enough to give some idea regarding the spread to be expected.

Mixtures

28. A common additive to primary explosives is potassium chlorate. A number of experiments were run to determine the sensitivity of such mixtures as a function of the percentage of potassium chlorate. The results are plotted on Plate 16. It will be noted that, in the case of diazodinitrophenol, the most sensitive mixture for .0001 inch wire is quite different from that for .00029 inch wire. Thus, as might be expected, the activation energy evidently changes with the proportions of the mixture. Perhaps the most striking feature of the curves on Plate 16 is their dissimilarity, which indicates the impracticability of making any predictions at the present stage of the investigation. The lead thiocyanate - potassium chlorate mixtures are, of course mixtures of two non-explosives.

Explosive Preparation

29. As previously noted, it has been found necessary to grind the explosive in a ball mill. Since no equipment was available for the measurement of subsieve particles sizes of primary explosives, an experiment was run to determine the relationship between milling time and sensitivity. The explosive used was lead styphnate loaded at 3400 psi and both .0001 inch and .00029 inch tungsten wire were used (.030 inches long). The results are presented in the following tabulation.

Milling Time (hours)	Energy Requirement (ergs) for Wire Diameter of .0001 inch	.00029 inch
2		1160 - 1235
16	177-194	1030-1095
48	158-179	902-1015
112	149-162	895-946

The values given are the fifty percent firing energies plus and minus their standard deviations. This experiment was run while the glass bottles previously referred to were still in use. It will be noted that

the sensitivity increases with grinding time. The explosive was wet with chloroform during grinding. The data are represented graphically on Plate 17. A rather surprising sequel to this experiment was one in which the same explosives were loaded after standing in the chloroform for eight or nine days after grinding. With .0001 inch bridgewires the values obtained with material which had been ground 16, 48 and 112 hours were 160-173, 154-171, and 162-172 respectively. The milling time had no significant effect upon the sensitivity, where the material was stored under chloroform for several days after grinding. Although there has been some speculation regarding the reason for this behavior, the correct explanation is in doubt.

Loading Pressure

30. A brief experiment was run to determine the effect of loading pressure. The results are presented graphically on Plate 18. The increase in energy requirement with loading density is too small to be of importance from a practical point of view so that ruggedness considerations, etc. should be the controlling factors in the choice of loading pressures.

Reproducibility

31. Of utmost importance to the designer considering the use of the low energy spray metal type primer in his fuze designs is the reproducibility in firing characteristics that can be expected. This is particularly true in fuzes where two primers of different energy requirements are utilized in the same fuze. Tables IV and V show a record of a number of tests conducted over a three year period. From this an idea of the reproducibility and the spread of firing energies can be gleaned. However, in surveying these tables it should be kept in mind that during the past three years there has been considerable improvement in firing equipment such as switches and firing chambers and in the resistance measuring technique for the reduced diameter tungsten wire. Hence if these factors have led to less circuit losses and more uniform primers, the most recent primers should show lower energies and less spread. In commenting on the results obtained with the Tophet-C wire it is pertinent to remark that the 139 ohm/in. wire used in the more recent primers was not entirely uniform. As the spool was used, the resistance became higher and the firing energy of the bridged primers became lower indicating a gradual reduction of the wire diameter.

Initiation Times

32. Measurements have been made of the time intervals between the firing pulse and a signal received from a probe which is outside of but close to the output end of the initiator. Most of these measurements were made in connection with specific problems in the application

of the initiators so that the data are somewhat spotty and disconnected. The time measured includes the time taken for the disturbance to reach the probe and for the timing device to respond as well as the time between firing pulse and explosion. Two different probe systems (shown on Plate 19) as well as two types of timers were used. The data obtained with one arrangement may not be directly comparable to those obtained with another.

33. The data plotted on Plates 20 and 21 were obtained using the arrangement shown in Figure (1) Plate 19. Those on Plate 20 and the lead azide data on Plate 21 were obtained with a vacuum thermocouple timing circuit similar to that described in Reference (g). The data on Plate 21 for initiators with lead styphnate flash charges were obtained with a Potter Counter Chronograph. The data plotted on Plate 22 were obtained using the arrangement shown in Figure (2) Plate 19. In obtaining these data a Potter Timer was used with amplifiers similar to those used with the timing circuit described in Reference (h).

34. It will be noted that the initiators with lead azide flash charges are much faster than those with lead styphnate flash charges although previous sections have shown lead azide to be much less sensitive. This is in agreement with the general experience that reactions of lead azide grow to detonation with very short burning periods if any at all.

Constant Current Firing

35. Although a large number of firing mechanisms for electric primers accomplish the firing by an energy surge (such as a discharge from a charged capacitor) through the primer bridge, it is often of interest to know something of the current firing characteristics under conditions of negligible change of current with time. It is fairly obvious, for example, that during the course of fabrication of electric primers the primer resistance must be taken as a quality control, and this usually involves the passage of current through the bridge wire while it is surrounded with sensitive explosive. An inquiry into the firing characteristics of primers under constant current passage would indicate among other things, the maximum current which can be safely used in such tests.

36. If one considers a wire of diameter D, resistance, R, and length, l, passing a steady current I then the energy input in a unit time will be given by I^2R and this will be expended by useful heat conveyance through the wire's peripheral surface and heat lost through the wire's end surface. If the heat loss through the wire's ends is neglected one may write:

Equation (2) $$I^2R = \pi D l c_1 \Delta T$$

where c_1, is a surface conductivity factor and ΔT the temperature drop between the wire and the explosive.

Substituting for R its equivalent value of $\frac{kl}{D^2}$ we obtain $I^2 \frac{kl}{D^2} = \pi D l C_1 \Delta T$

or $$\Delta T = \frac{kI^2}{D^3}$$

Assuming that the explosive has a constant ignition temperature, then the threshhold firing current should equal: $I_f = K_2 D^3/2$. That such a simple relationship does not exist for primers of very small bridge length becomes apparent from an analysis of experimental data such as that plotted on Plate 23. The fifty percent firing point for each diameter and length was obtained using a "Bruceton" test procedure involving between 40 and 50 samples for each point plotted. Current passage was maintained for a period of 10 seconds before a shot was called a failure.

37. From Plate 23 one may deduce that there is considerable heat lost through the wire ends; if this were not so the current for firing should be independent of the bridge length (the power input per unit length of bridge is independent of the length as length and resistance are directly proportional). The fact that bridges of the same diameter but different length require different currents is attributable to different heat loss through the wire ends. It should be noted also that as the bridge diameter gets larger the end losses also get larger (the curves diverge). This effect is in agreement with the expectations because the ratio of the end area to the surface area ($\frac{D^2}{2} \Big/ \pi D l = \frac{D}{2 l}$) for a given length increases with increasing diameter.

38. If equation (2) is modified to account for end losses we obtain:

$$\text{eq.(3)} \quad \frac{I^2 k_1 \ell}{D^2} = k_2 D \ell \Delta T + k_3 D^2 \Delta T$$

$$\text{or} \quad \Delta T = \frac{k_1 I^2 \ell}{k_3 D^4 + k_2 D^3 \ell}$$

This equation at present would be extremely difficult to solve for several reasons:

(1) The wire temperature for explosion is an unknown function of the diameter.

(2) k_1, the resistivity of the wire material and k_3, its thermal conductivity are functions of the temperature.

(3) The relation between the surface coefficient of heat transfer between the wire and the explosive (k_2) and the temperature is not known and may be important. k_2 may also be a function of time.

Perhaps data of another type, such as the energy for firing by condenser at long RC times, or a measure of the time to fire along with the current to fire under constant current firing conditions may be combined to

yield a solution for the quantity T in the above equations and a value of R for the primer. Until such a time equation (3) is of hypothetical interest only. The data presented on Plate 23 are plotted in a different fashion on Plate 24.

CONCLUSIONS

39. The conclusions which can be drawn from the data discussed above are summarized below:

(1) That the threshold energy requirement of electric initiators is roughly proportional to the volume of the bridgewire. For minor adjustments this is quite precise.

(2) That, to effect initiation of explosives, small diameter bridgewires must be raised to higher temperatures than larger wires. This effect is more pronounced for some explosives than for others.

(3) That the threshold energy requirement is inversely related to the rate of delivery of energy except where the energy is delivered in a very short time. An initiator, of 100 micro-inch diameter wire which will fire on an energy of the order of 100 ergs must have this energy delivered within about 5 microseconds. The shape of the pulse apparently has little effect.

(4) That an increase in either particle size or loading density will increase the energy requirement, the latter only slightly.

(5) That the addition of potassium chlorate will sensitize some explosives to initiation by a hot wire.

(6) That the steady state current sensitivity of fine wire, short bridge length initiators, does not change as rapidly with bridge diameter as does the pulse energy sensitivity. The latter varies practically directly with the volume or square of the diameter while the former varies with about the 3/2 power of the diameter (see slope of Plate 24).

(7) That the fastest initiation is not necessarily obtained with the most sensitive explosive. Lead azide, which is one of the most insensitive materials tested, is by far the fastest, when initiated with a sufficiently vigorous pulse.

40. None of the above statements is particularly startling. Most of them are predictable from relatively simple basic considerations or had been determined for other types of electric initiators in the past. The principles which govern the performance of spraymetal electric initiators are the same as those which govern that of all wire bridge initiators. The advantage of the spraymetal process is that it gives the designer an unprecedented control of the factors which, in turn, control performance.

41. The data presented herein do not, in general, refer to initiators which are ready for release as practical fuse components. For the designer of fuzes this memorandum gives some indication of what characteristics might be expected of electric initiators of this type. For the designer of primers and detonators the information herein can be used as a starting point in the development of a new item. The considerations discussed in this memorandum are obviously only a few of those which must be taken into account in the design of a device for use in ordnance. Other considerations, such as surveillance, compatibility and mechanical ruggedness, and the incorporation of the initiators in primers and detonators, are left for future memoranda.

R. Stresau

R. STRESAU

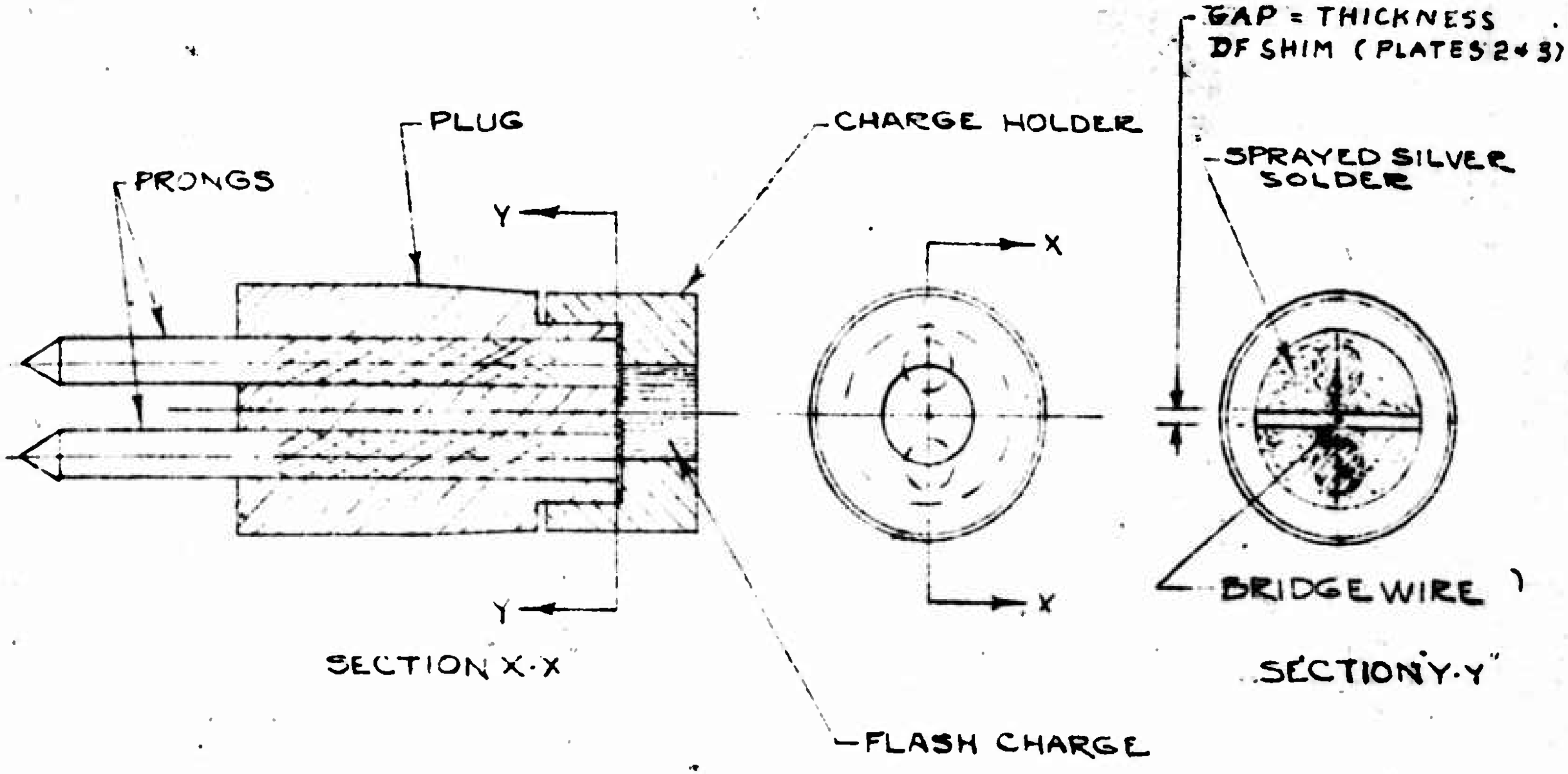
I. Kabik

I. KABIK

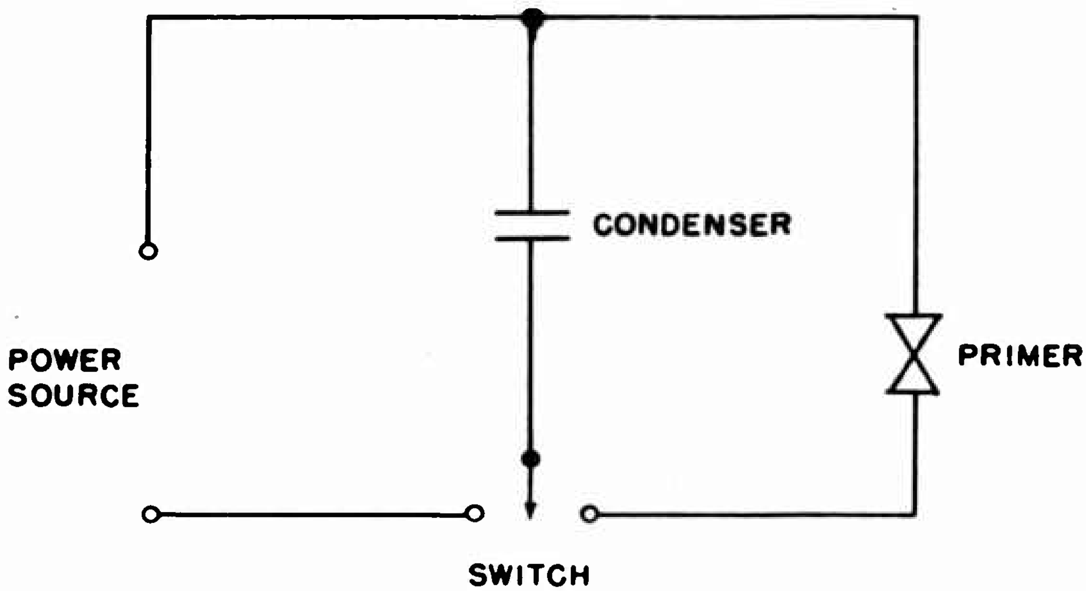
L. D. Hampton

L. D. HAMPTON

RS:IK:LDH/ces



ELECTRIC INITIATOR ASSEMBLY

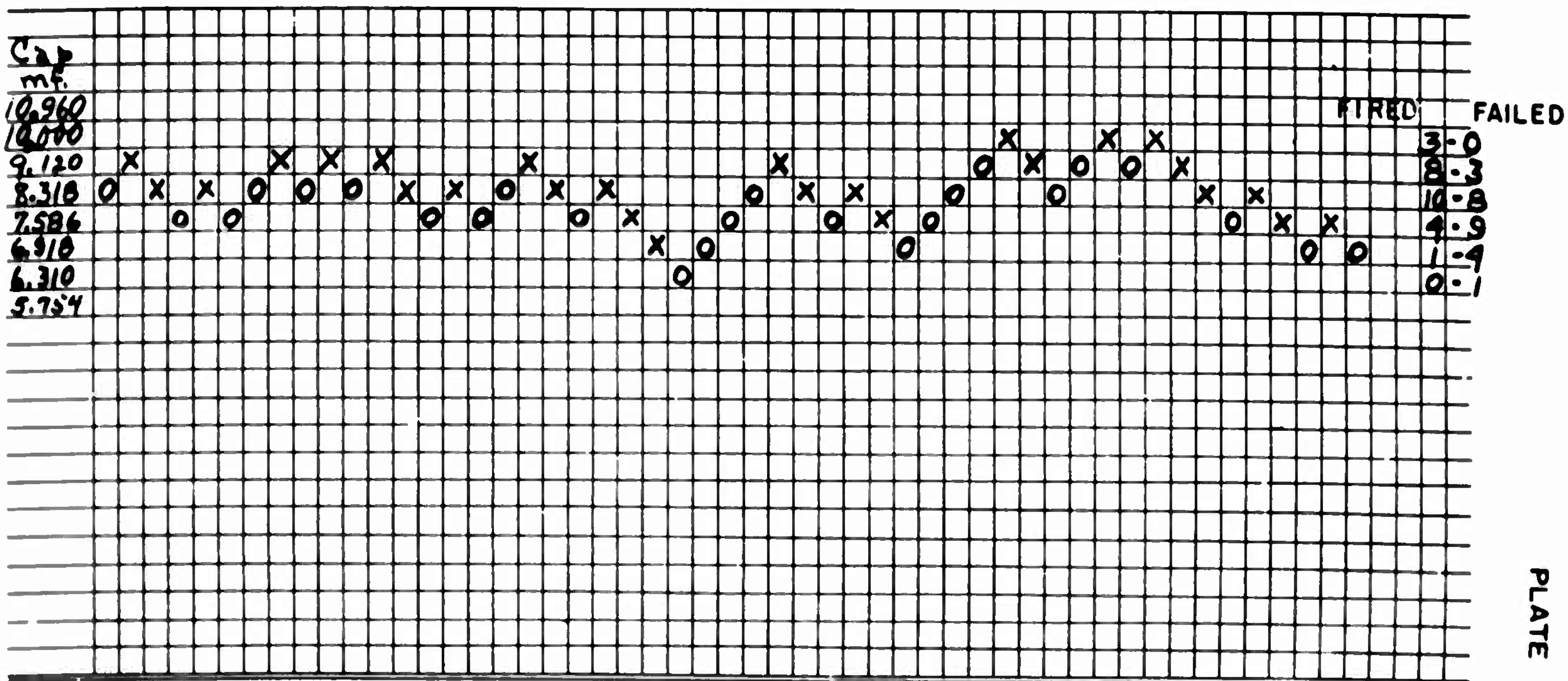


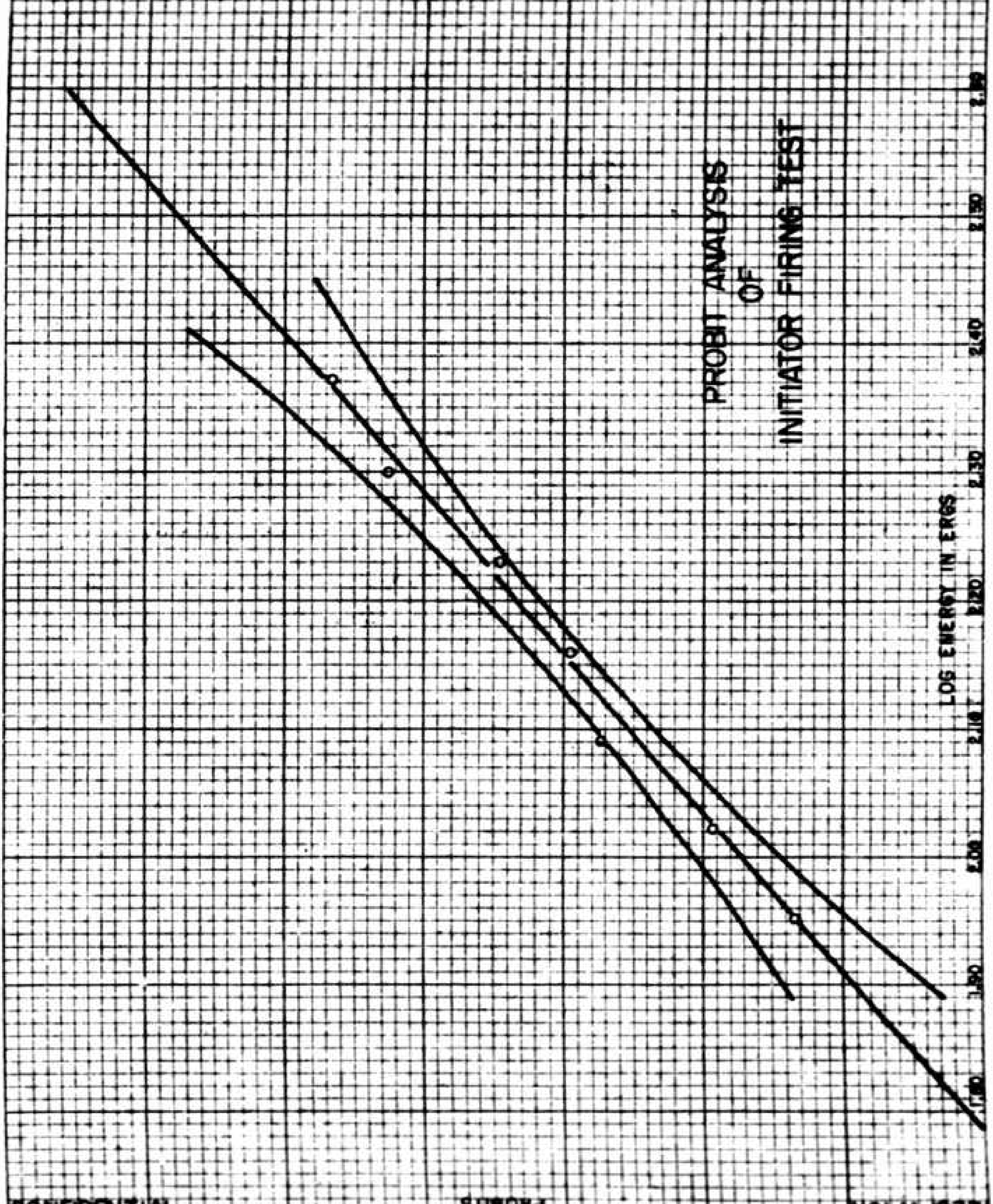
CIRCUIT FOR EXPERIMENTAL CONDENSER DISCHARGE FIRING OF LOW ENERGY ELECTRIC PRIMERS

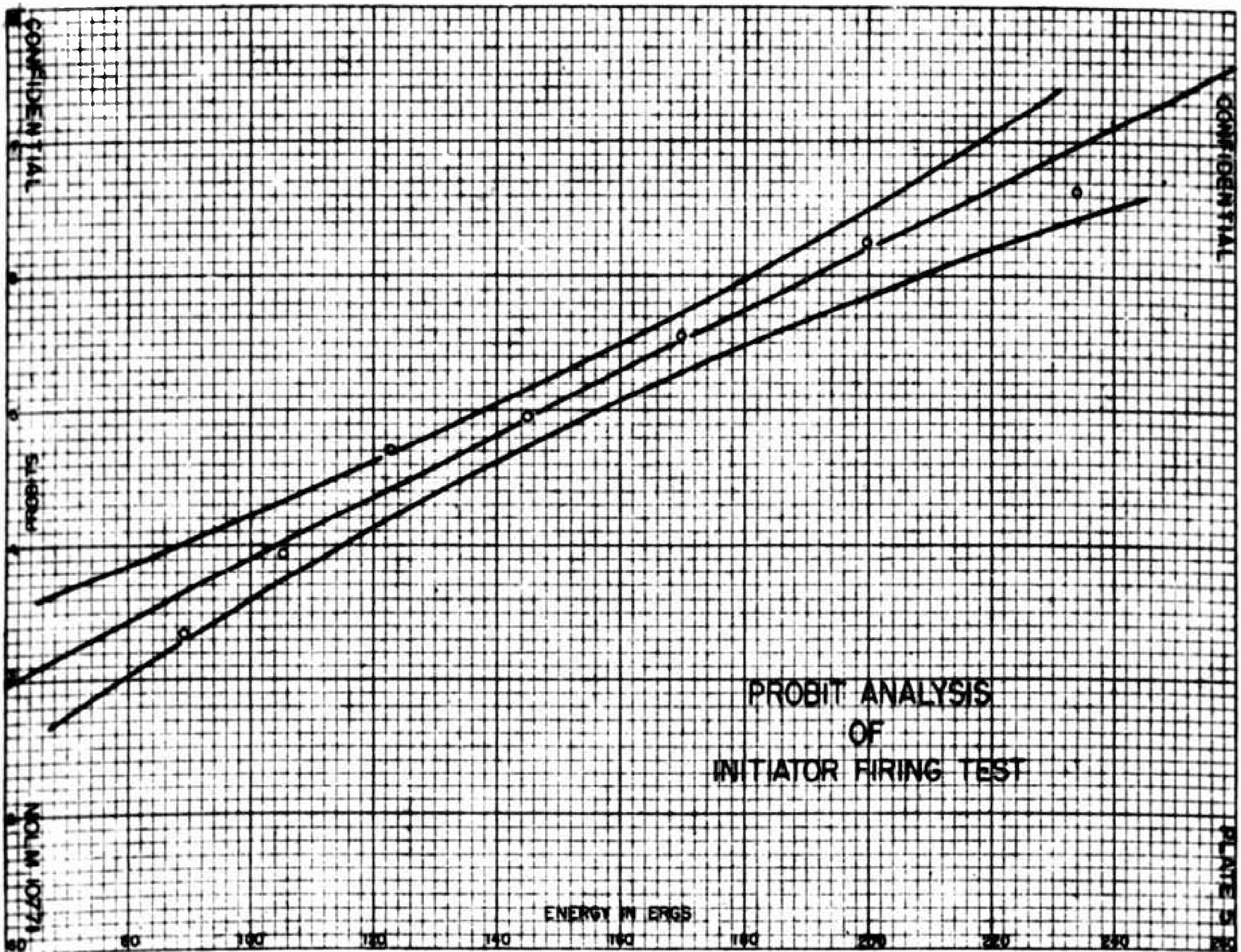
EXPLOSIVES SENSITIVITY TEST

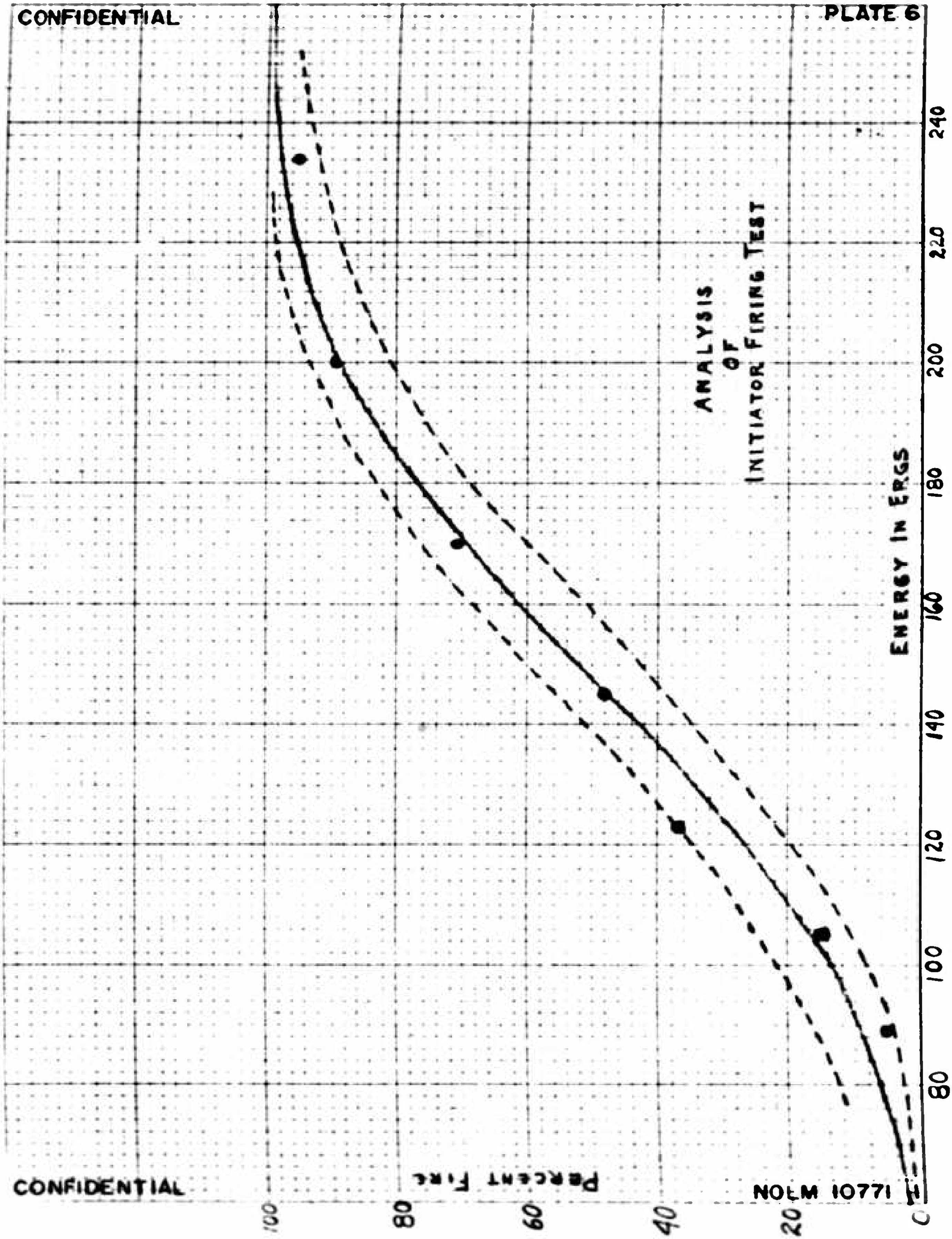
Bruceton Test Sheet

BRIDGEWIRE WORK ORDER NUMBER	LOADING WORK ORDER NUMBER	BATCH NUMBERS
FLASH CHARGE MATERIAL: LEAD STYPHNATE	POTENTIAL: 3.5 volt	CAPACITANCE
CURRENT	STEP SIZE: Log C_1/C_2 = 0.040	DATE OF TEST: NOV 12, 1946
BRIDGE: PA6-30	MILLED	
RESULTS MEAN: MEAN 8.560 mf. S = 1.80 STEPS	TESTED BY: L.D.H.	
DONOR SIZE	ACCEPTOR SIZE	
REMARKS		

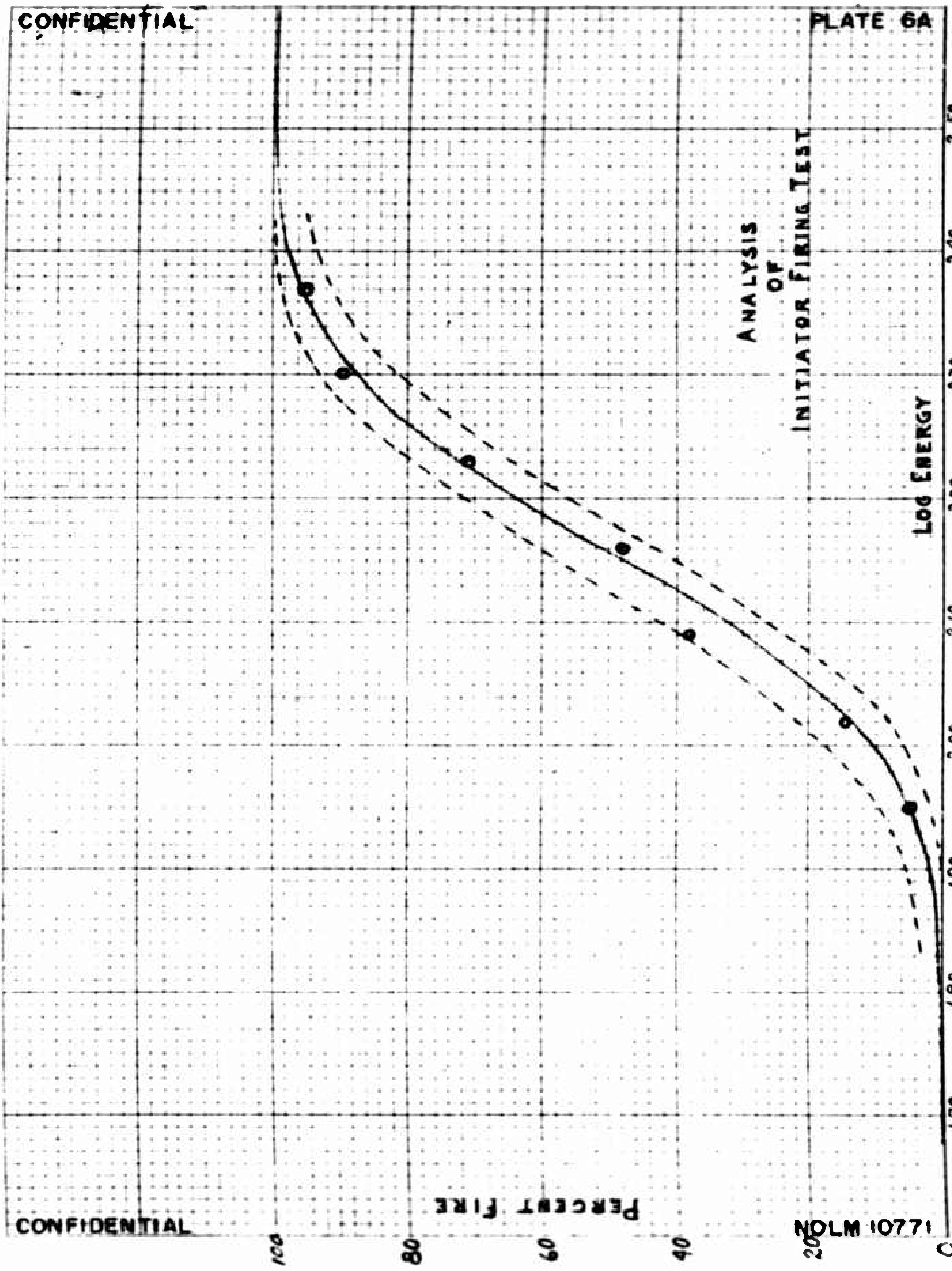


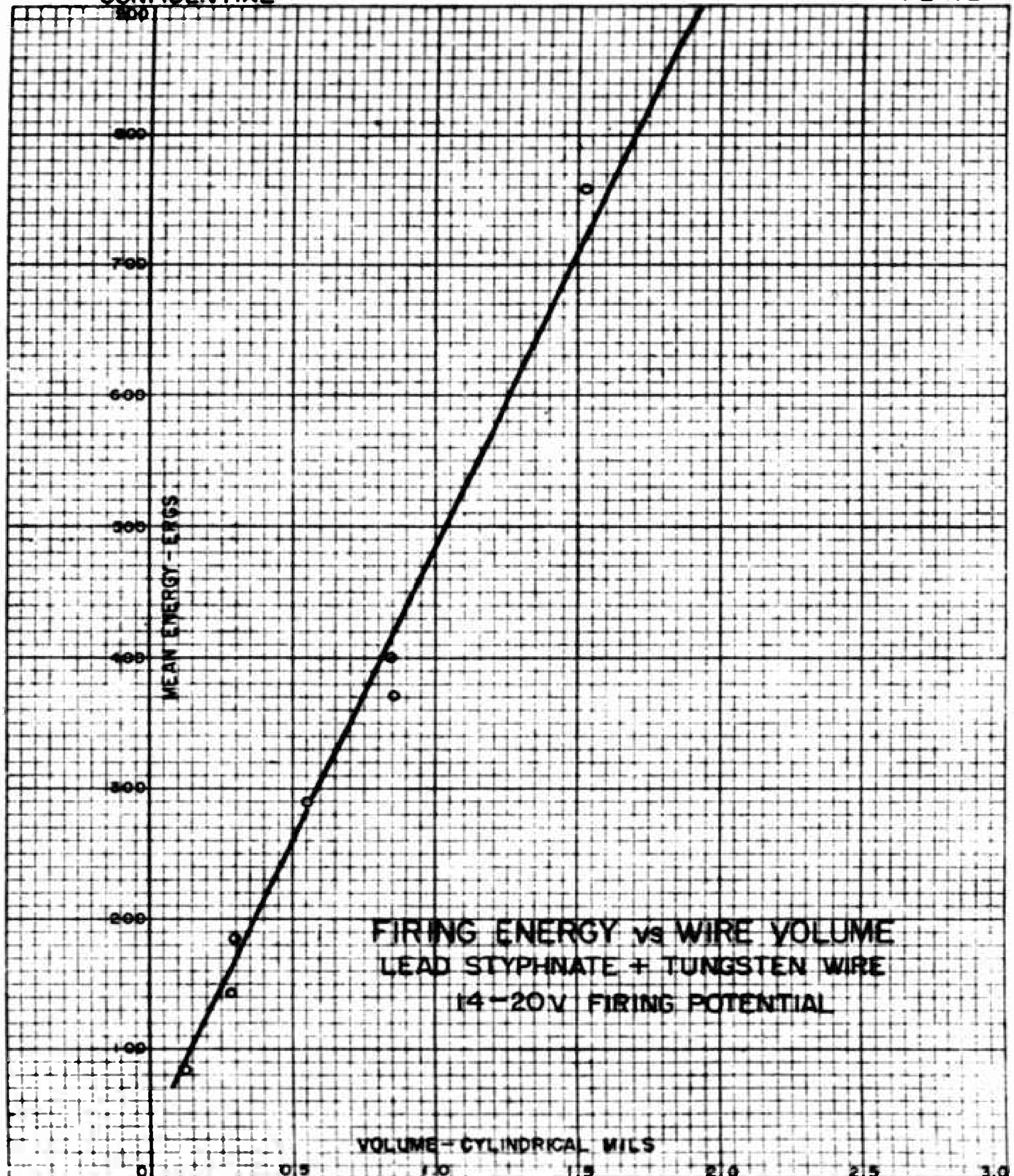

PROBIT ANALYSIS
OF
INITIATOR FIRING TEST
LOG ENERGY IN ERGS
2.40
2.30
2.00
PROBITS

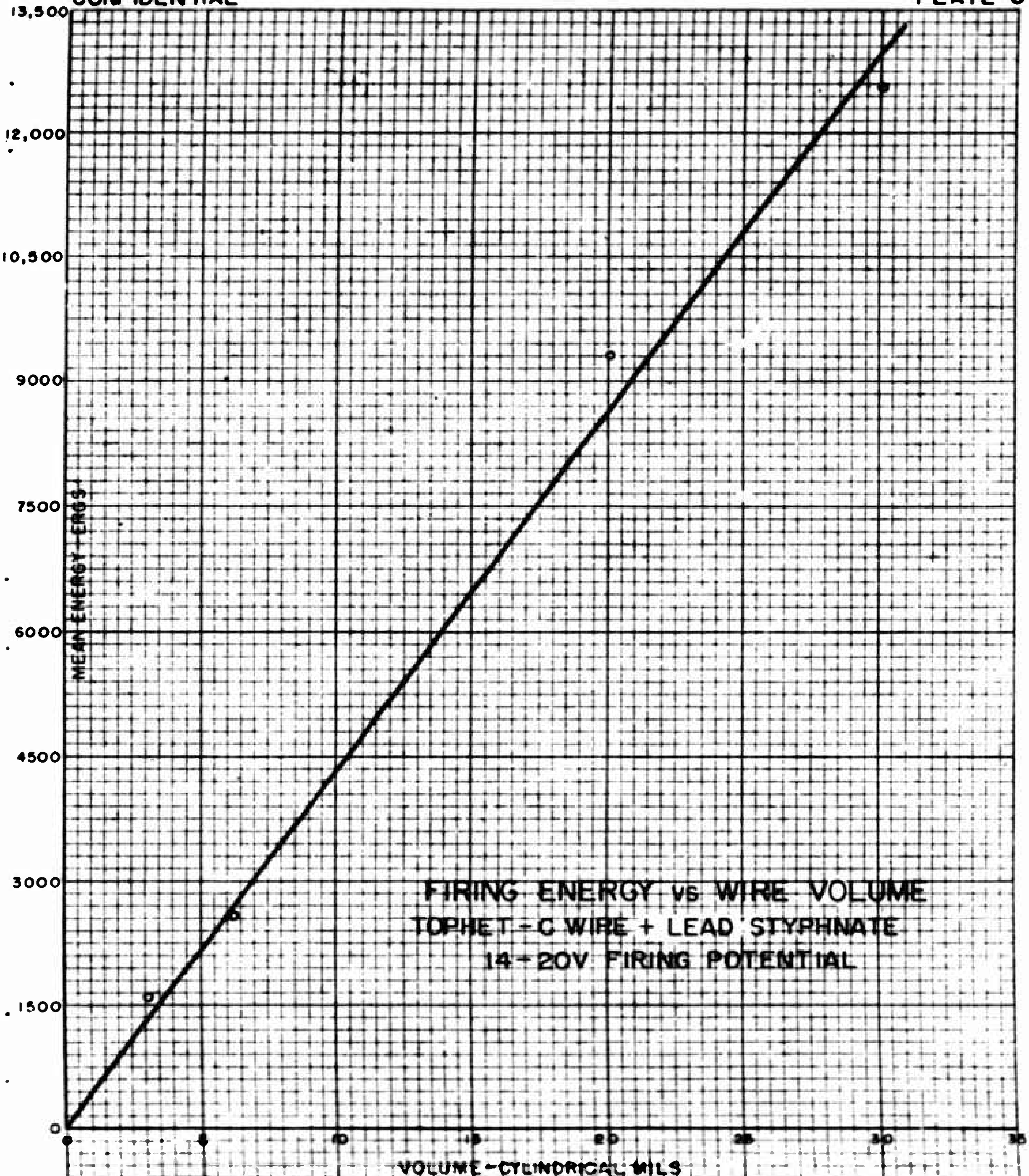

PROBIT ANALYSIS
OF
INITIATOR FIRING TEST
PROBITS
ENERGY IN ERGS
60
80
100
120
140
160
180
200
220
240
260


ANALYSIS
OF
INITIATOR FIRING TEST
ENERGY IN ERGS
PERCENT FIRE
80
100
120
140
160
180
200
220
240
0
20
40
60
80
100

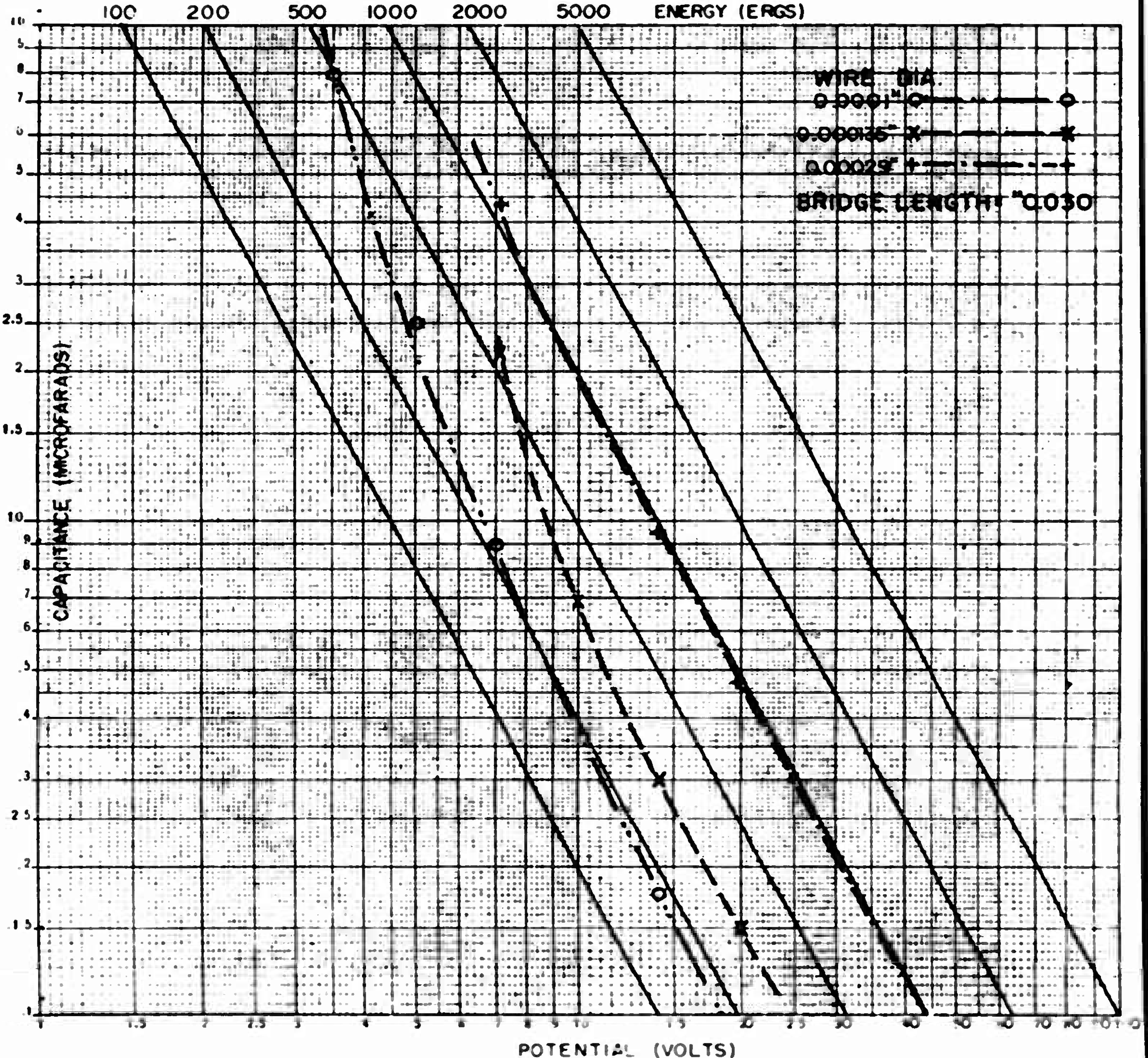
6

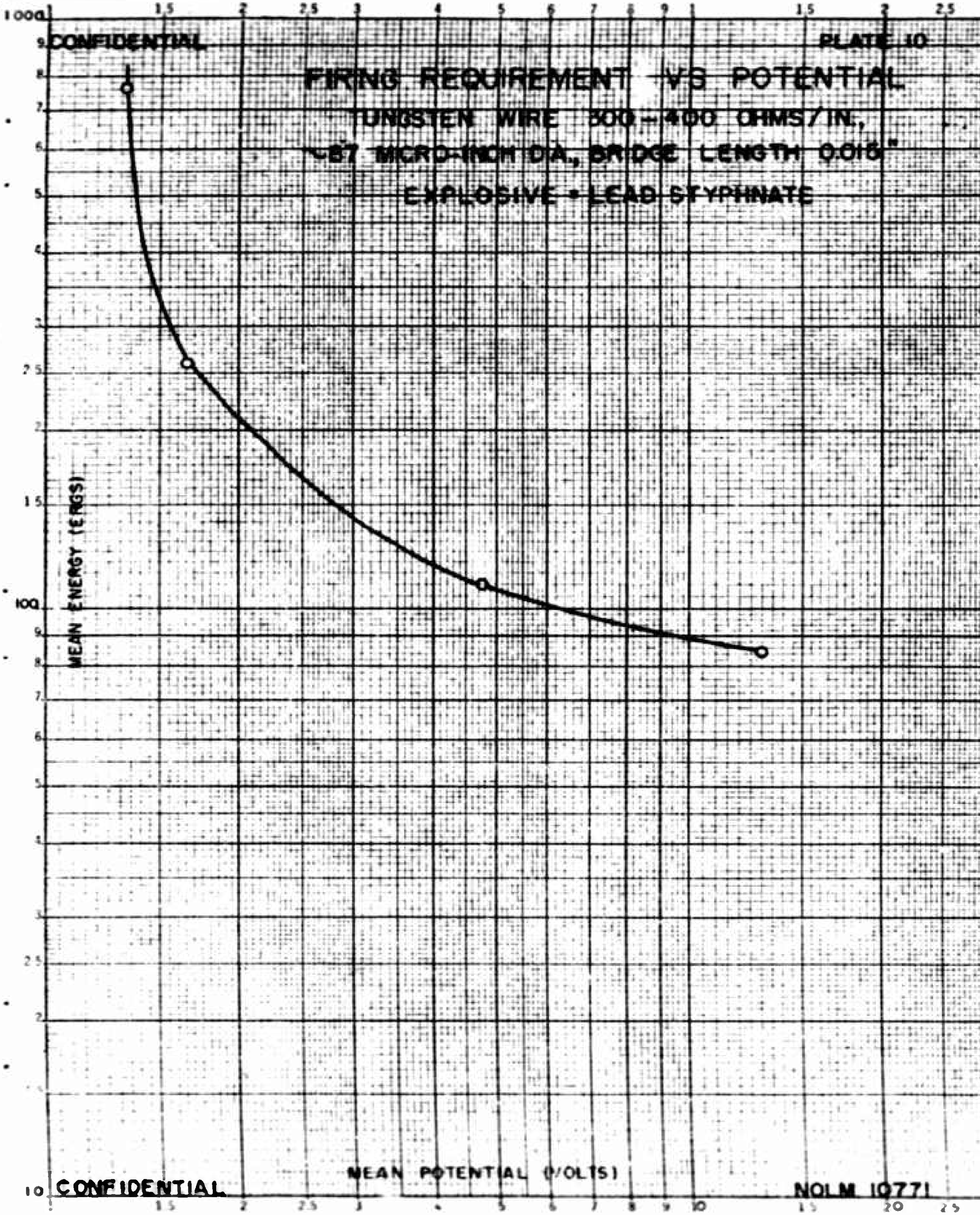

ANALYSIS
OF
INITIATOR FIRING TEST
LOG ENERGY
PERCENT FIRE
100
80
60
40
20
0
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50

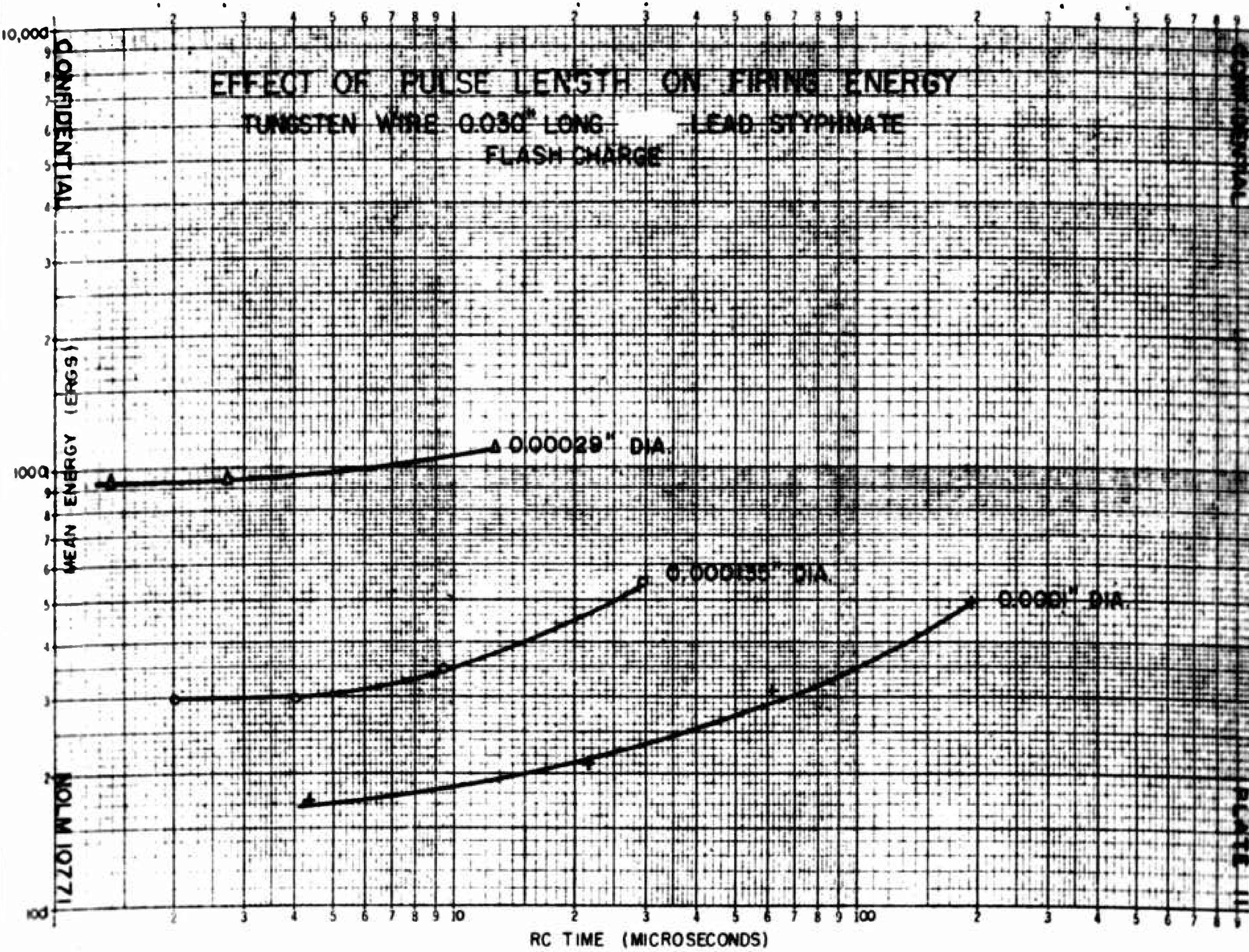

FIRING ENERGY vs WIRE VOLUME
LEAD STYPHNATE + TUNGSTEN WIRE
14-20V FIRING POTENTIAL
MEAN ENERGY-ERGS
VOLUME-CYLINDRICAL MILS
900
800
700
600
500
400
300
200
100
0
0.5
1.0
1.5
2.0
2.5
3.0

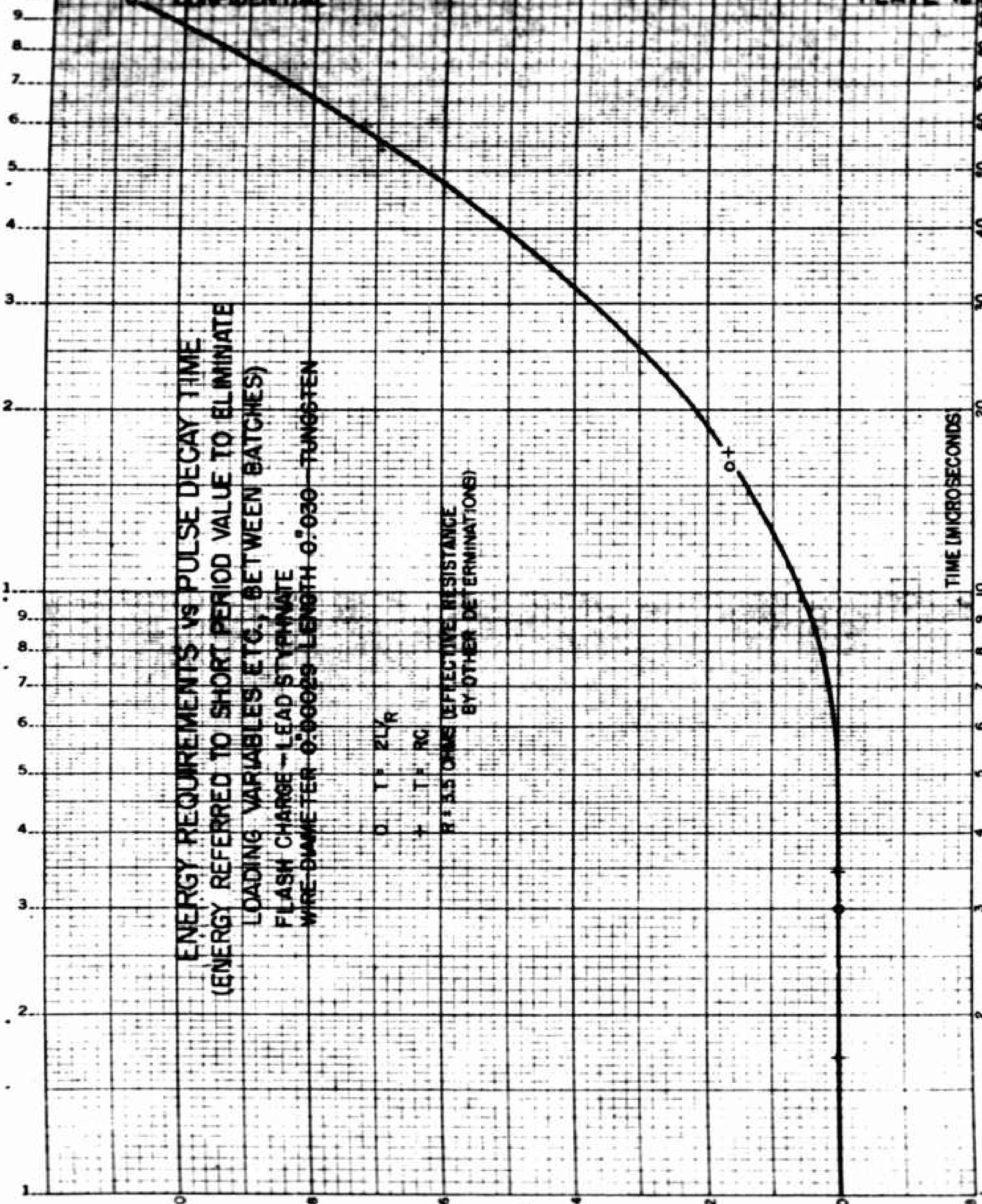

13,500
12,000
10,500
9000
7500
6000
4500
3000
1500
0
MEAN ENERGY - ERGS
0
5
10
15
20
25
30
35
VOLUME - CYLINDRICAL MILS
FIRING ENERGY vs WIRE VOLUME
TOPHET - C WIRE + LEAD STYPHNATE
14 - 20V FIRING POTENTIAL

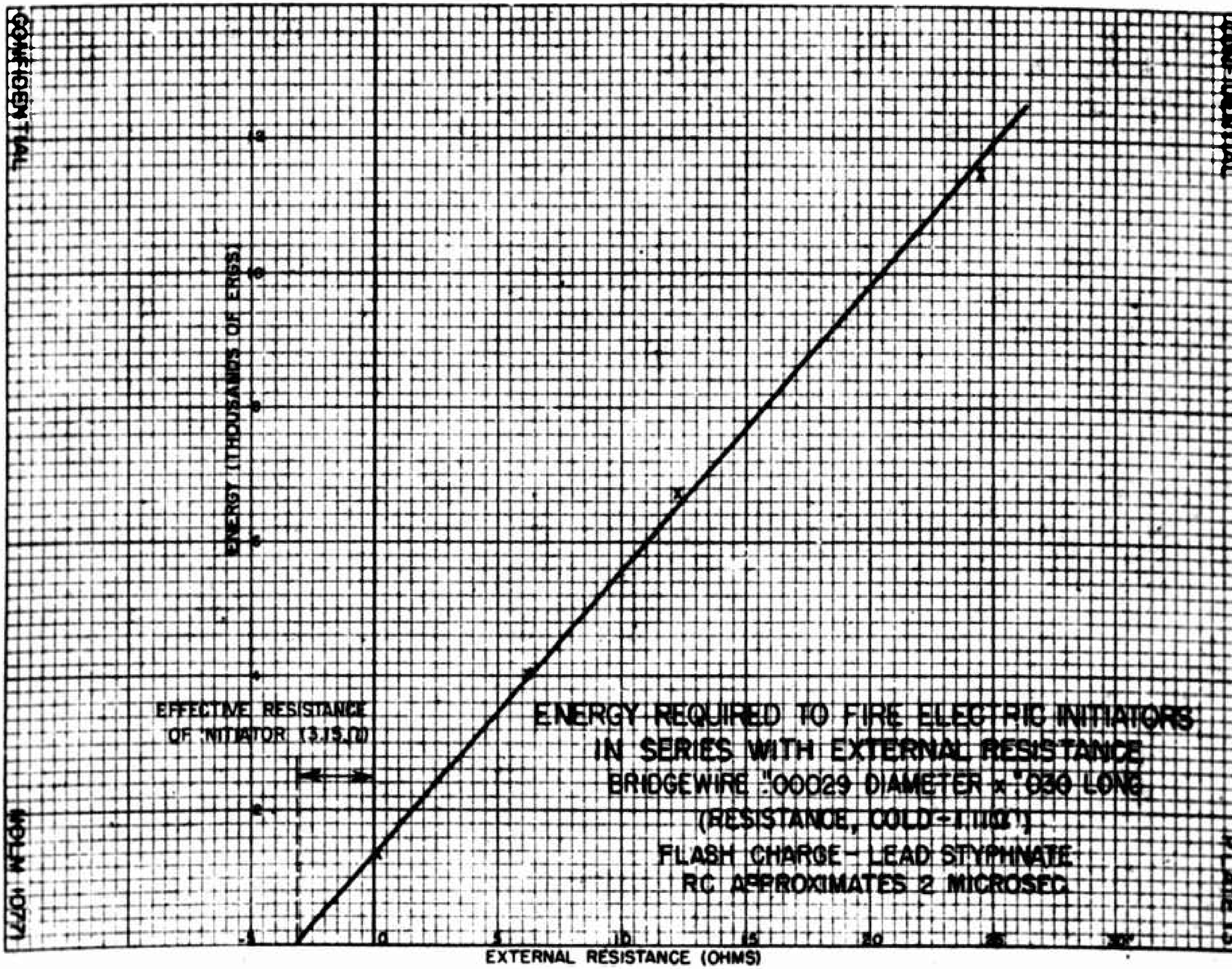
CAPACITANCE REQUIRED FOR 50% FIRING VS POTENTIAL FOR ELECTRIC INITIATORS WITH TUNGSTEN WIRE OF VARIOUS DIAMETERS. FLASH CHARGE - LEAD STYPHNATE

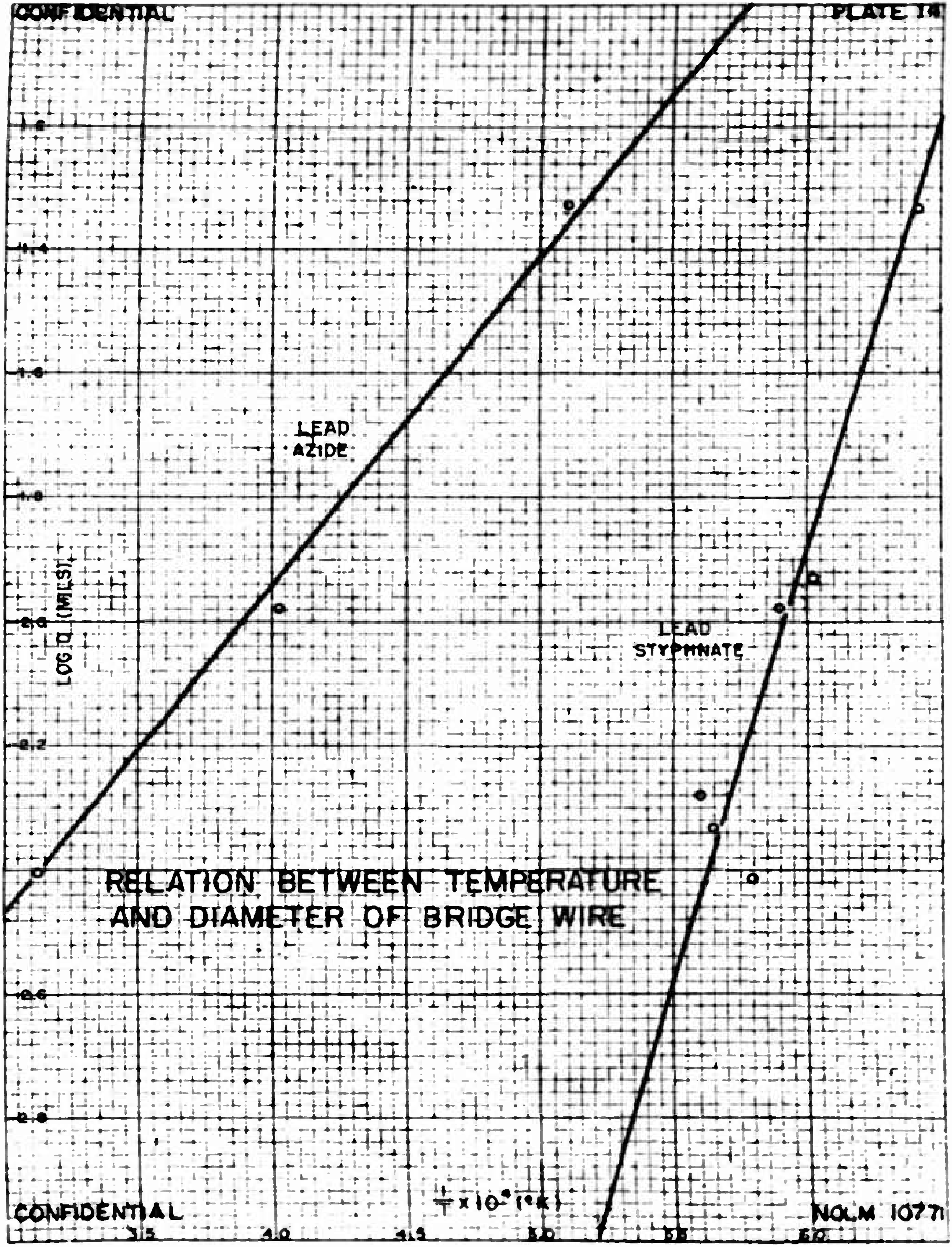



FIRING REQUIREMENT VS POTENTIAL
TUNGSTEN WIRE 300-400 OHMS/IN.,
~87 MICRO-INCH DIA, BRIDGE LENGTH 0.016"
EXPLOSIVE - LEAD STYPHNATE
MEAN ENERGY (ERGS)
MEAN POTENTIAL (VOLTS)
1000
100
10
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25

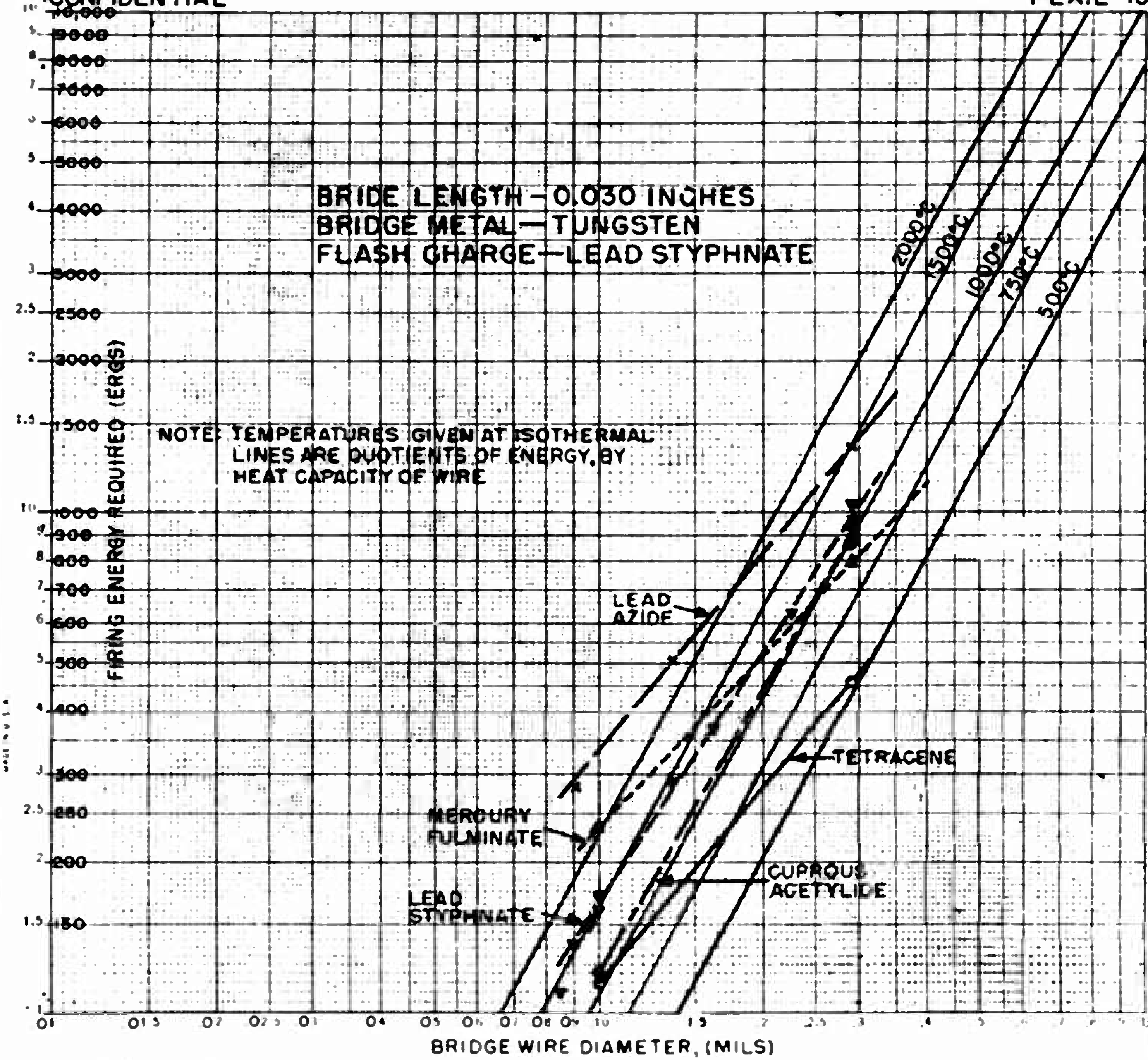

EFFECT OF PULSE LENGTH ON FIRING ENERGY
TUNGSTEN WIRE 0.030" LONG LEAD STYPHNATE
FLASH CHARGE
0.00029" DIA.
0.000135" DIA.
0.0001" DIA.
MEAN ENERGY (ERGS)
RC TIME (MICROSECONDS)
10,000
1000
100
10


ENERGY REQUIREMENTS vs PULSE DECAY TIME
(ENERGY REFERRED TO SHORT PERIOD VALUE TO ELIMINATE
LOADING VARIABLES ETC., BETWEEN BATCHES)
FLASH CHARGE – LEAD STYPHNATE
WIRE DIAMETER 0.00029 LENGTH 0.030 TUNGSTEN
O T = 2L/R
+ T = RC
R = 3.5 OHMS (EFFECTIVE RESISTANCE
BY OTHER DETERMINATIONS)
TIME (MICROSECONDS)
E/E₀


ENERGY REQUIRED TO FIRE ELECTRIC INITIATORS
IN SERIES WITH EXTERNAL RESISTANCE
BRIDGEWIRE ".00029 DIAMETER x ".030 LONG
(RESISTANCE, COLD = 1.11Ω)
FLASH CHARGE – LEAD STYPHNATE
RC APPROXIMATES 2 MICROSEC.
EFFECTIVE RESISTANCE
OF INITIATOR (3.15 Ω)
ENERGY (THOUSANDS OF ERGS)
EXTERNAL RESISTANCE (OHMS)
-5
0
5
10
15
20
25
30
2
4
6
8
10
12



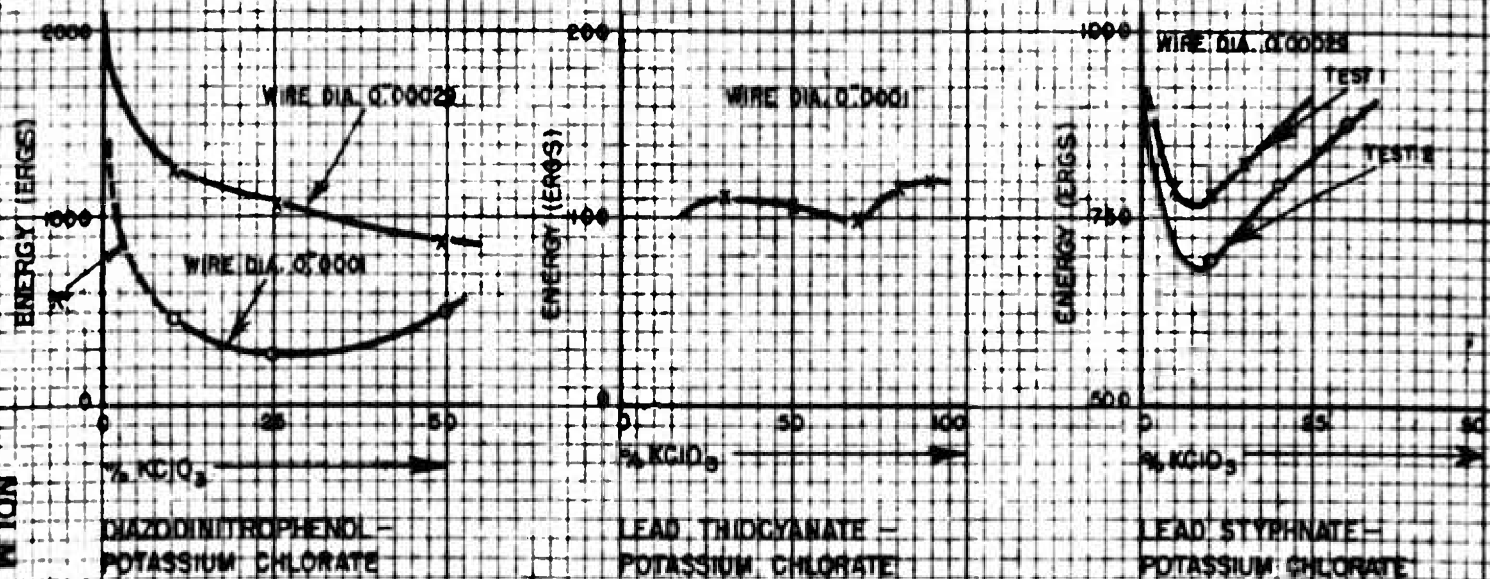
RELATION BETWEEN TEMPERATURE AND DIAMETER OF BRIDGE WIRE

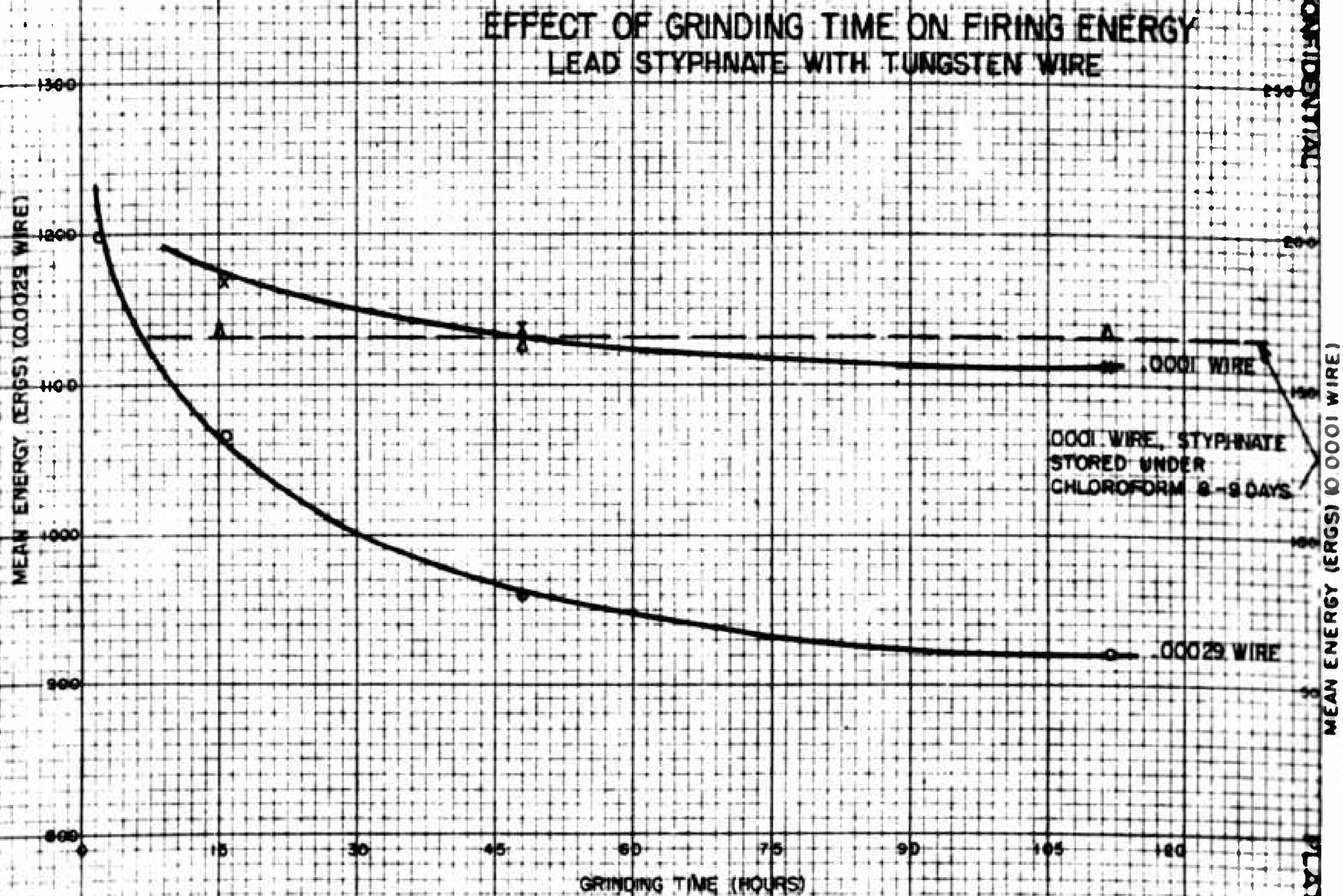

BRIDE LENGTH — 0.030 INCHES
BRIDGE METAL — TUNGSTEN
FLASH CHARGE — LEAD STYPHNATE
NOTE: TEMPERATURES GIVEN AT ISOTHERMAL LINES ARE QUOTIENTS OF ENERGY, BY HEAT CAPACITY OF WIRE
2000°C
1500°C
1000°C
750°C
500°C
LEAD AZIDE
TETRACENE
MERCURY FULMINATE
CUPROUS ACETYLIDE
LEAD STYPHNATE
FIRING ENERGY REQUIRED (ERGS)
BRIDGE WIRE DIAMETER, (MILS)

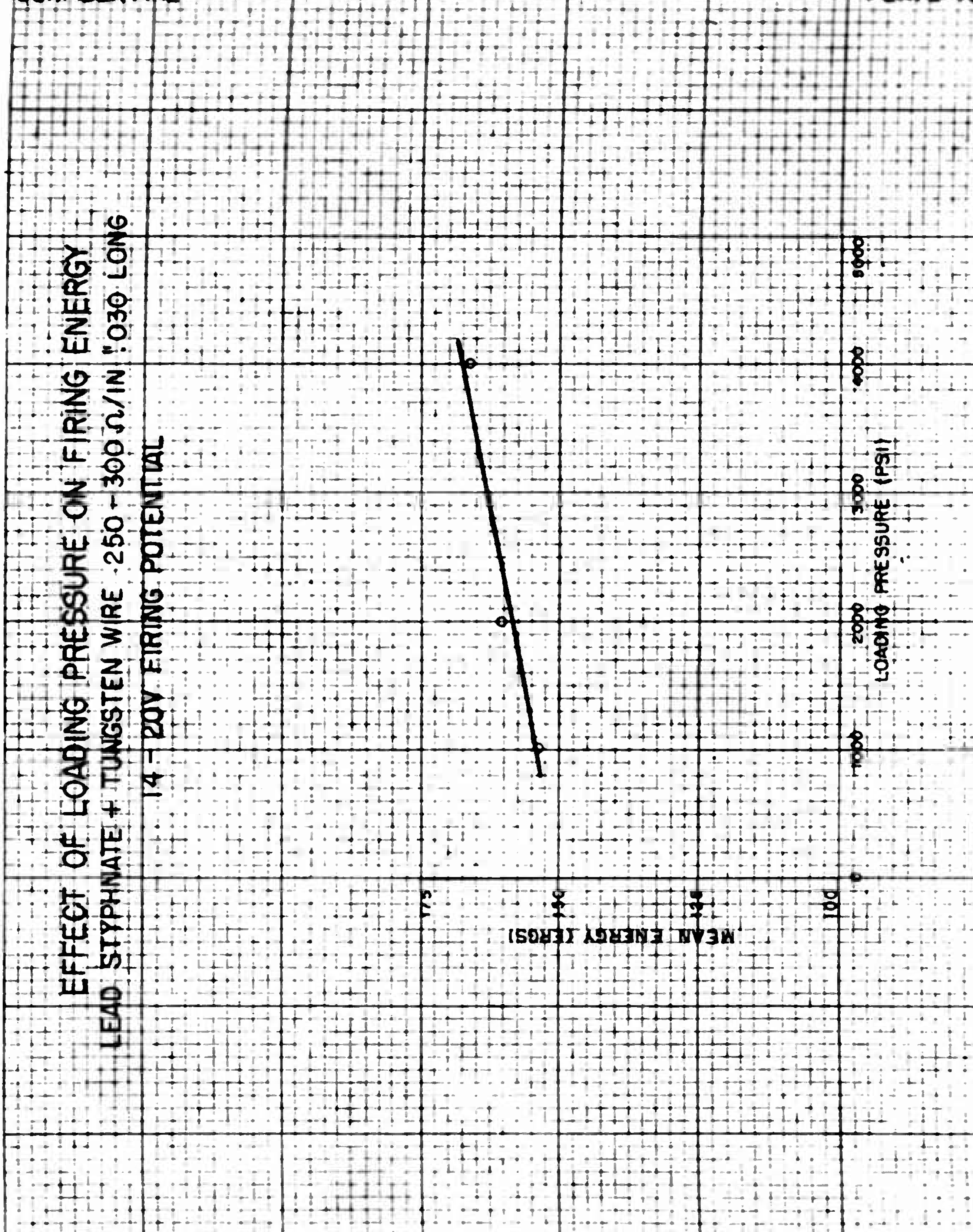
ENERGY REQUIREMENTS AS A FUNCTION OF COMPOSITION FOR SOME BINARY MIXTURES LOADED IN SPRAY METAL BRIDGED ELECTRIC INITIATORS

* WITH NO POTASSIUM CHLORATE, THE 0."0001 BRIDGE WIRE BURNED OUT WITHOUT INITIATING THE EXPLOSIVE.

NOTE: THE "DDNP" USED HAD DARKENED IN STORAGE. SOME DECOMPOSITION PRODUCTS PROBABLY PRESENT.




EFFECT OF GRINDING TIME ON FIRING ENERGY
LEAD STYPHNATE WITH TUNGSTEN WIRE
MEAN ENERGY (ERGS) (0.0029 WIRE)
1300
1200
1100
1000
900
800
MEAN ENERGY (ERGS) (0.0001 WIRE)
250
200
150
100
50
0
15
30
45
60
75
90
105
120
GRINDING TIME (HOURS)
.0001 WIRE
.0001 WIRE, STYPHNATE STORED UNDER CHLOROFORM 8-9 DAYS
.00029 WIRE


EFFECT OF LOADING PRESSURE ON FIRING ENERGY
LEAD STYPHNATE + TUNGSTEN WIRE .250-.300 Ω/IN .030 LONG
14 - 20V FIRING POTENTIAL
LOADING PRESSURE (PSI)
0
1000
2000
3000
4000
5000
MEAN ENERGY (ERGS)
175
150
125
100

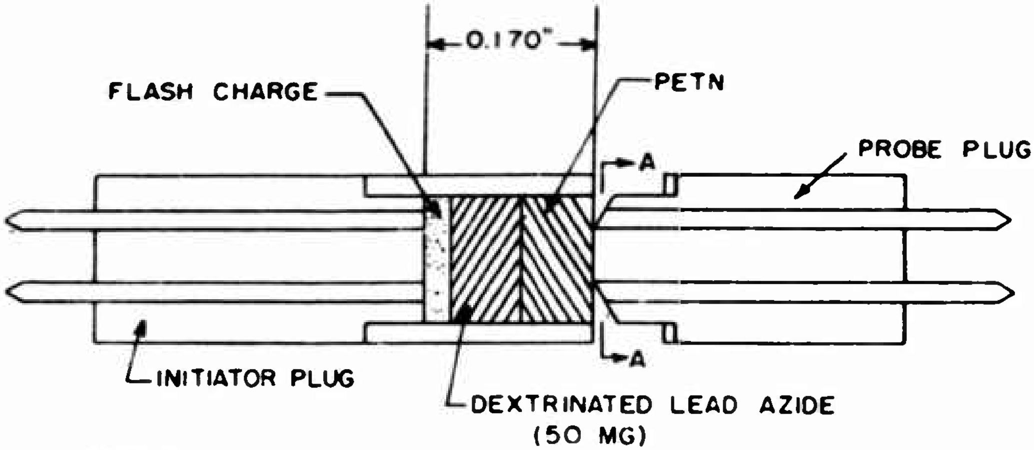
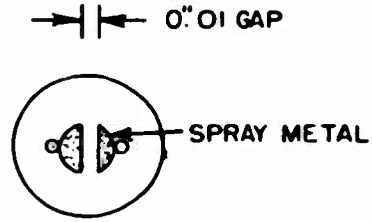


FIG. 1



SECTION A–A

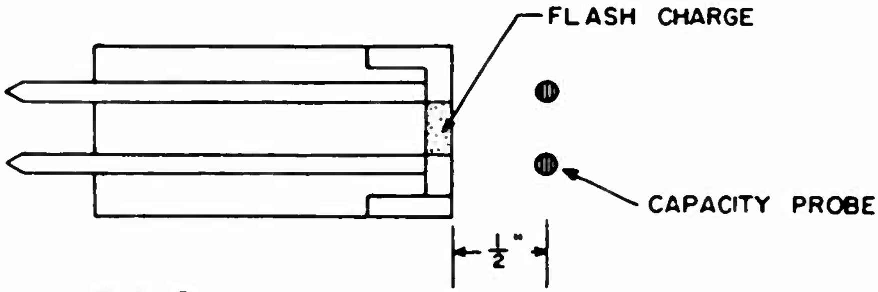
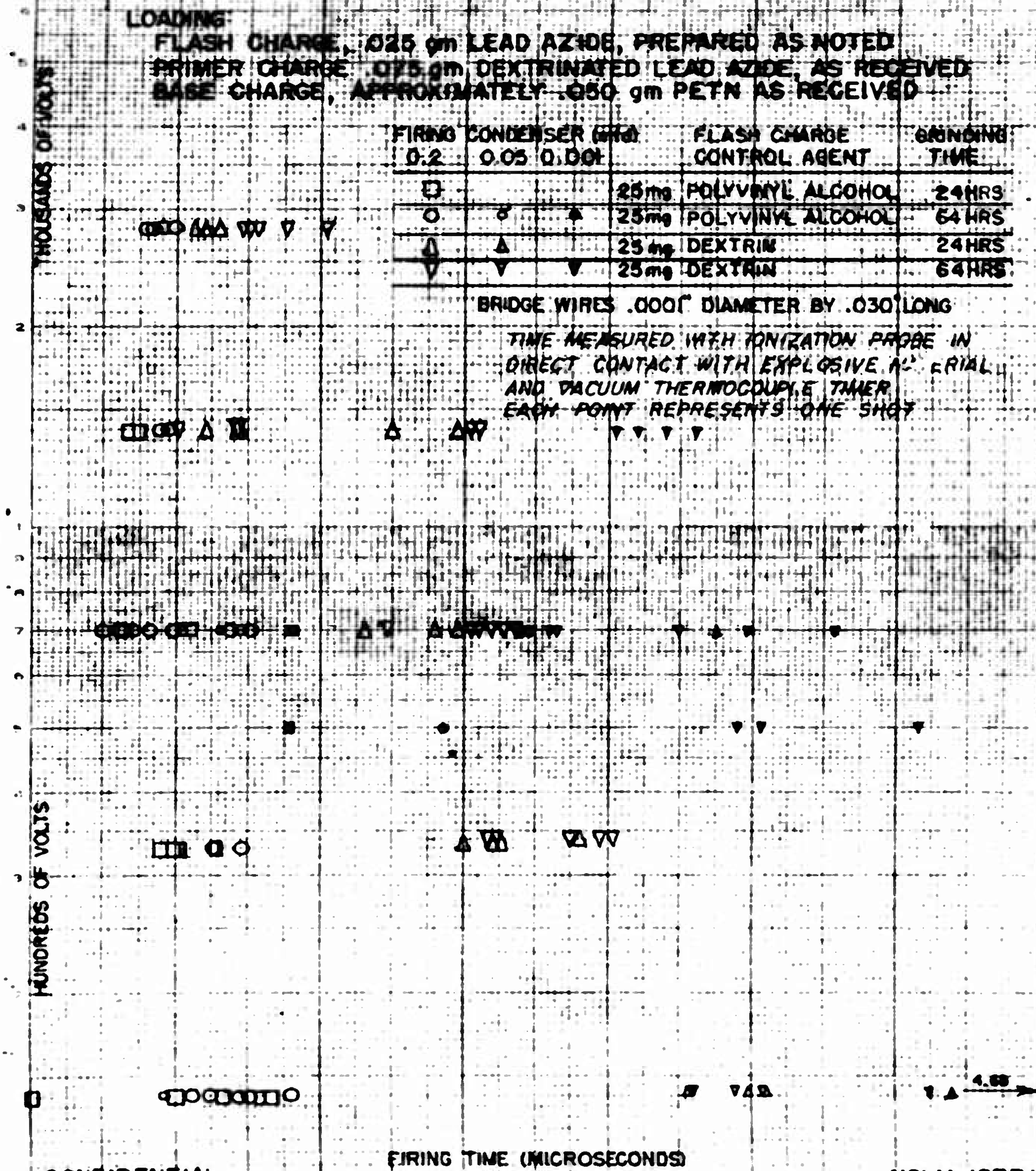


FIG. 2

PROBE SYSTEMS FOR MEASURING FIRING TIME OF SPRAY METAL PRIMERS

FIRING TIMES OF ELECTRIC INITIATORS vs FIRING VOLTAGE
(CONDENSER DISCHARGE FIRING USING VACUUM SWITCH)



FIRING TIMES OF ELECTRIC INITIATORS vs FIRING VOLTAGE

(CONDENSER DISCHARGE FIRING USING VACUUM SWITCH)

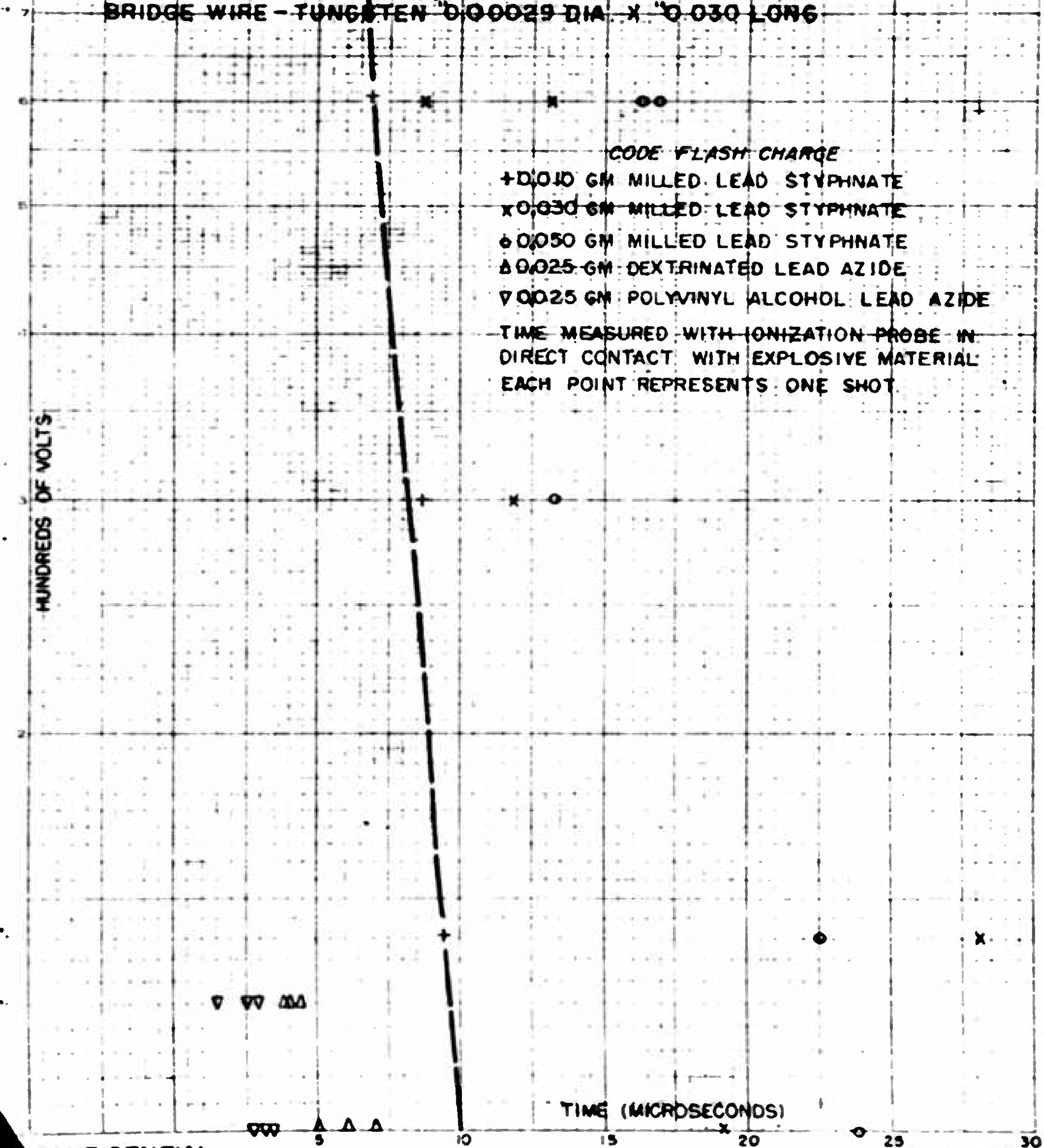
LOADING: FLASH CHARGE AS NOTED

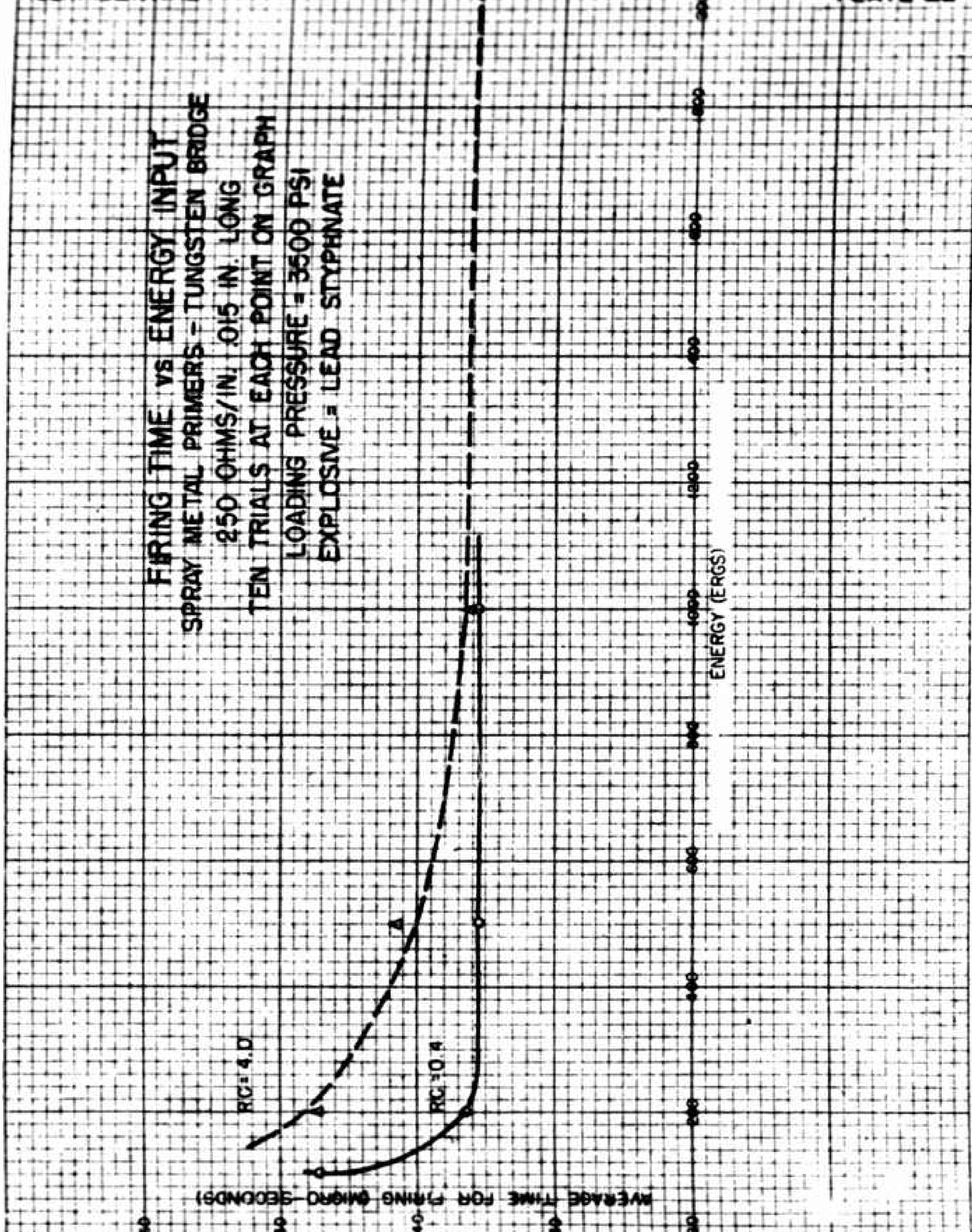
PRIMER CHARGE .050 gm DEXTRINATED LEAD AZIDE, AS RECEIVED

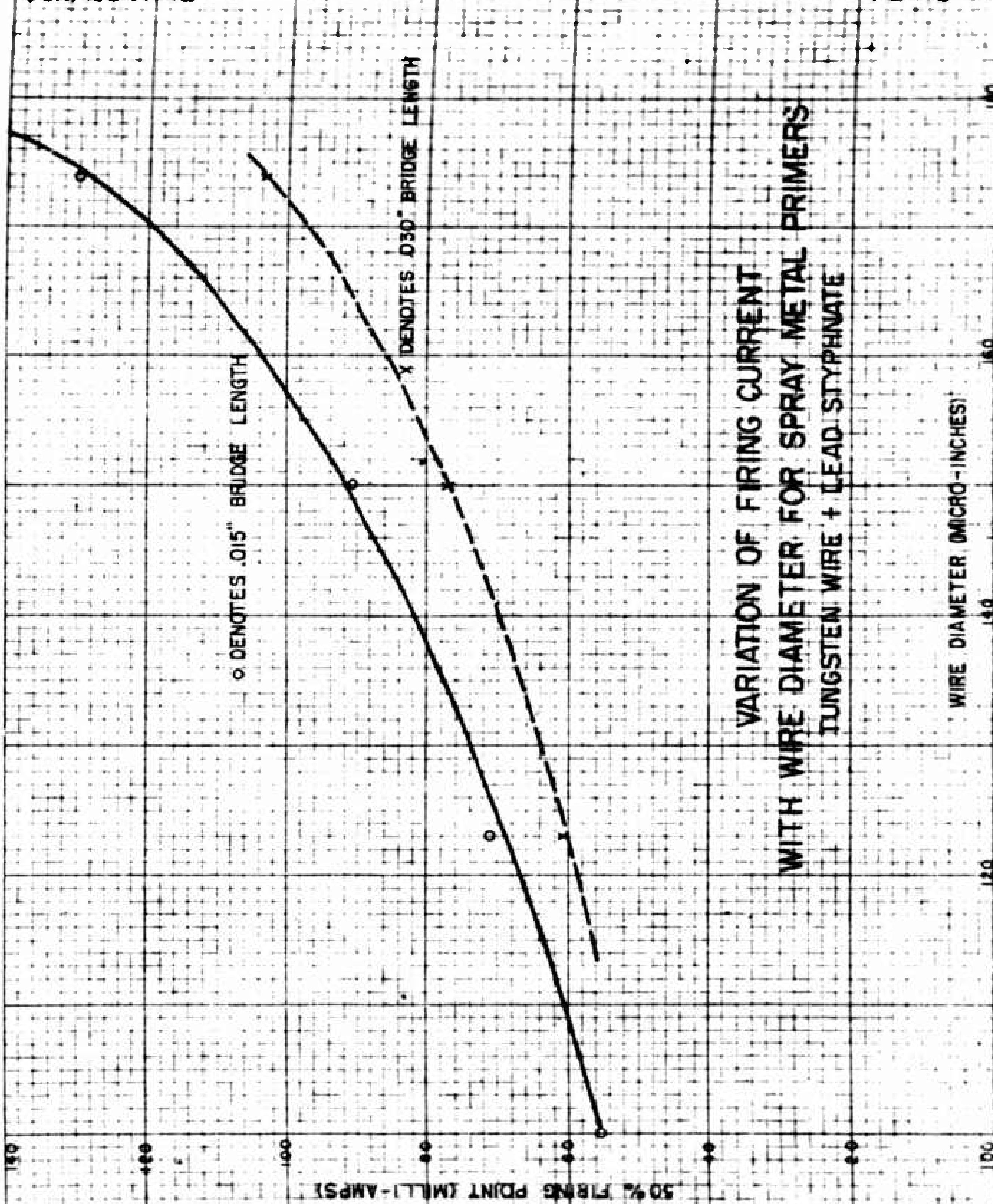
BASE CHARGE .050 - .080 gm PETN AS RECEIVED

FIRING CONDENSER 0.050 mfd

BRIDGE WIRE - TUNGSTEN 0.00029 DIA. X 0.030 LONG




FIRING TIME vs ENERGY INPUT
SPRAY METAL PRIMERS - TUNGSTEN BRIDGE
250 OHMS/IN. .015 IN. LONG
TEN TRIALS AT EACH POINT ON GRAPH
LOADING PRESSURE = 3500 PSI
EXPLOSIVE = LEAD STYPHNATE
RC=4.0
RC=0.4
ENERGY (ERGS)
AVERAGE TIME FOR FIRING (MICRO-SECONDS)


VARIATION OF FIRING CURRENT
WITH WIRE DIAMETER FOR SPRAY METAL PRIMERS
TUNGSTEN WIRE + LEAD STYPHNATE
o DENOTES .015" BRIDGE LENGTH
x DENOTES .030" BRIDGE LENGTH
WIRE DIAMETER (MICRO-INCHES)
50% FIRING POINT (MILLI-AMPS)

VARIATION OF FIRING CURRENT WITH WIRE DIAMETER

SPRAY METAL PRIMERS USING TUNGSTEN WIRE WITH LEAD STYPHNATE FLASH CHARGE

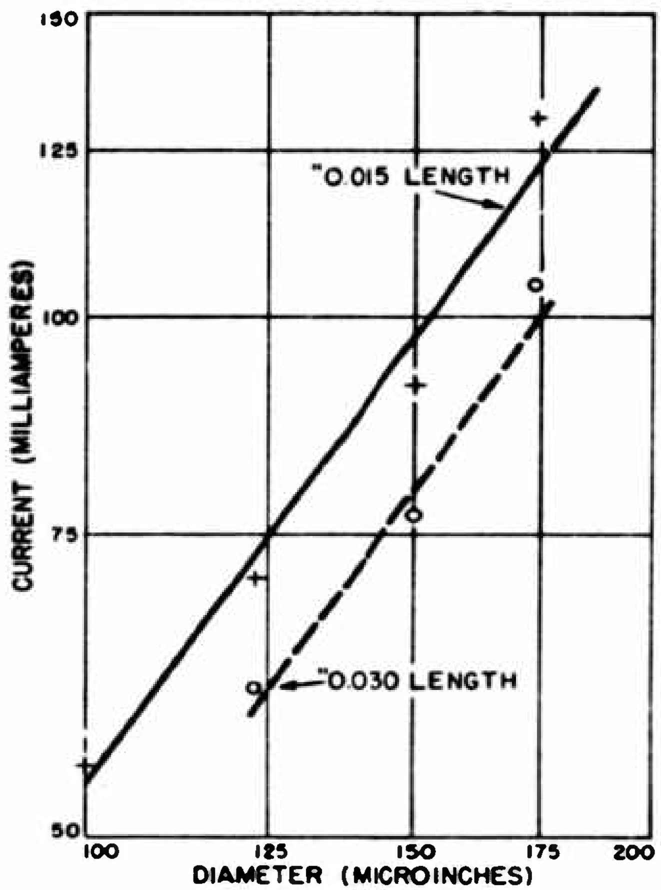


TABLE I

INITIATORS PREDICTED TO FIRE ON BASIS OF LOG ENERGY COMPARED WITH PREDICTION ON BASIS OF ENERGY

Energy (Ergs)	Log E	Number Tested	Number Fired	Predicted Firings From Log E	Predicted Firings From Energy	
76	1.88	45	0	0.2- 2.0	0.9	5.1
89	1.95	42	2	0.8- 4.6	1.9	6.9
105	2.02	42	6	3.4- 9.3	4.4	10.6
123	2.09	41	16	9.5-16.4	8.8	15.6
145	2.16	49	24	21.6-29.7	19.5	27.5
170	2.23	39	28	25.4-31.6	23.8	30.3
200	2.30	37	33	29.8-34.7	29.7	34.8
234	2.37	41	39	37.1-40.4	38.1	40.7
		Chi Square		0.396	5.022	

TABLE II

MEAN ENERGY REQUIREMENTS OF ELECTRIC INITIATORS WITH BRIDGES OF VARIOUS DIMENSIONS

Explosive-Lead Styphnate* Preparation-Milled 16-24 hrs

Diam (Mils)	Length (Mils)	Vol. (V) (Cyl. Mils)#	Resistance Wire (ohms/in)	Resistance Initiator (ohms)**	Material	Energy Req. (Q) (ergs)	Q/V
.065	3	0.013	650	2	Tungsten	11*	867
.095	10	0.090	300+	3+	"	57	632
.087	15	0.114	300-400	4.5	"	86	757
.095	30	0.271	300+	9+	"	145	535
.100	30	0.300	275	8.25	"	185	617
.135	30	0.547	145	4.35	"	290	530
.168	30	0.847	97	3	"	370	437
.290	10	0.841	35	0.35	"	400	475
.225	30	1.52	54	1.6	"	760	500
.290	30	2.52	35	1.05	"	950	376
.450	15	3.04	241	3.6***	Tophet "C"	1600	526
.450	30	6.08	241	7.2	"	2600	428
1.0	30	30.	50	1.5	"	13000	433

\# A cylindrical mil is the volume of a cylinder one mil long by one mil in diameter.

* The first (11 erg) initiators shown on the table were loaded with a 60/40 mixture of lead thiocyanate/potassium chlorate. No figures have been obtained for lead styphnate with this size wire.

** Calculate cold values are given, measured values are somewhat higher.

*** Tophet "C" is an alloy similar to Nichrome. There are, of course, tolerances in the composition which result in variations in resistivity. The diameters given are calculated on the basis of a resistivity of 100 microhm cm.

TABLE III

MEAN ENERGY REQUIREMENTS OF ELECTRIC INITIATORS LOADED WITH VARIOUS FLASH CHARGE EXPLOSIVES

Tungsten Bridge 30 mils Long

EXPLOSIVE	MEAN ENERGY REQUIREMENT (ERGS) 0.1 mil Diam	0.29 mil Diam.
Silver Acetylide	95	-
Lead Thiocyanate/Potassium Chlorate 40/60	100	----
Tetracene	115	460
Lead Styphnate, Basic	125	700
Cuprous Acetylide	125	750-850***
Lead 2,4-Dinitroresorcinate, Normal	125	1175
Lead Styphnate/Potassium Chlorate 90/10	150	790
Lead Styphnate	160-225***	925-1290***
Lead 4,6-Dinitroresorcinate, Basic	180	1140
Lead 4,6-Dinitroresorcinate, Normal	190	1100
Lead 2,4-Dinitroresorcinate, Basic	210	1200
Mercury Fulminate	230	785
Diazodinitrophenol/Potassium Chlorate #75/25	260	1050
Lead 2 Nitroresorcinate, Normal	310	1260
Lead Azide	340 est ##	1340
Diazodinitrophenol/Potassium Chlorate #50/50	460	860
Diazodinitrophenol/Potassium Chlorate #90/10	460	1230
Diazodinitrophenol #	**	2100
Lead 2 Nitroresorcinate, Basic	*	2265

*Less than 50% fired at any energy used.

**Bridge burned out without firing DDNP.

***These values are extremes between which the means of several batches of slightly different preparation lie.

#This diazodinitrophenol was rather old stock, very dark in color, and probably contained an appreciable amount of decomposition products.

##Value interpolated from a graph which contains results obtained with both larger and smaller wire.

[redacted]

TABLE IV

REPRODUCIBILITY OF THE ENERGY REQUIREMENT OF SPRAY METAL-TYPE PRIMERS WITH TUNGSTEN WIRE BRIDGES

Resis (Ohms/in)	Length (in)	No. Tested	Test Date	Test Variable	Mean Firing Energy (ergs)	Std. Dev. (Log Units)	Std. Dev. at Mean + (Ergs)	Std. Dev. at Mean − (Ergs)	99% pt. (ergs)	1% pt. (ergs)	Remarks
140-150	.015	43	5/28/47	Capac. (V=14.1)	262	.1070	73	58	465	148	
140-150	.015	31	6/5/47	Capac. (V=14.1)	291	.0869	72	48	475	187	
200-250	.015	51	10/13/48	Voltage (C=0.1 mfd.)	100	.0881	50	33.2	258	39	
250-300	.015	51	10/14/48	Voltage (C=0.1 mfd.)	91	.0530	27	21	168	[illegible]	
250-300	.015	49	10/14/48	Voltage (C=0.1 mfd.)	81	.0225	8.3	8.3	102	[illegible]	Test Temp. + 120°F
250-300	.015	50	10/20/48	Voltage (C=0.1 mfd.)	85	.0538	25.2	17.5	153	48.5	Test Temp. - 40°F
250-300	.015	50	2/21/49	Capac. (V=14.1)	93	.1153	27.8	22.0	141	41	
250-300	.015	44	3/22/49	Capac. (V=14.1)	94	.040	9.0	8.1	117	76	
250-300	.015	46	12/13/49	Capac. (V=14.1)	84	.048	10.2	8.5	109	65	
250-300	.015	51	12/16/47	Capac. (V=14.1)	77	.1730	37.6	25.4	154	[illegible]	Made with commercial wire not quite within tolerance
300-400	.015	28	6/3/47	Capac. (V=14.1)	98	.1124	29	22	179	54	
300-400	.015	30	8/14/47	Capac. (V=14.1)	78	[illegible]	19	14	129	45	
300-400	.015	16	11/7/47	Capac. (V=14.1)	112	.0653	19	15	160	80	

TABLE V

REPRODUCIBILITY OF THE ENERGY REQUIREMENT OF SPRAY METAL TYPE PRIMER WITH TOPHET - C WIRE BRIDGES

Resis Nominal (Ohms/in)	Length (in.)	No. Tested	Test Date	Test Variable	Mean Firing Energy (ergs)	Std. Dev. (Log Units)	Std. Dev. at Mean (Ergs) +	Std. Dev. at Mean (Ergs) -	99% pt. (ergs)	1% pt. (ergs)	Remarks
80	.030	40	8/17/48	Capac. (V=50)	7188	.0733	1328	1113	10,407	4875	
139	.015	24	1/12/48	Capac. (V=40)	2880	.1360	1059	774	6,800	1362	
139	.030	29	11/7/47	Capac. (V=40)	4786	.0547	649	367	6,416	3371	
139	.030	29	6/18/27	Capac. (V=40)	4327	.0555	580	526	5,816	3208	
139	.030	51	10/6/48	Voltage (C=1 mfd)	5107	.0741	853	747	7,360	3610	Test Temp. + 14
139	.030	51	10/6/48	Voltage (C=1 mfd)	5107	.022	553	507	6,460	4030	
139	.030	50	12/7/48	Voltage (C=1 mfd)	4164	.0550	726	646	6,035	2860	Test Temp. -40°F
139	.030	53	2/21/49	Capac. (V=40)	3800	.0675	[illegible]	[illegible]	5,460	2650	
139	.030	50	11/8/49	Capac. (V=40)	3720	.061	562	488	4,[illegible]	2190	